Methods for climate change risk assessments:
An international knowledge review

Work Package 1 - Deliverable D1.1

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Authors: *Carlo Aall (eds.)*

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Short summary

The report identifies knowledge gaps on analysing climate change risks relating to the use of the impact chain framework, user-interface and stakeholder involvement, socio-economic scenarios and societal exposure to climate change and transboundary climate change impacts. The identified knowledge gaps are reformulated into several research questions to be addressed in the succeeding case-studies of the UNCHAIN project.

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Foreword

This is the first deliverable from the project "Unpacking climate impact chains. A new generation of action- and user-oriented climate change risk assessments" (UNCHAIN). The report contains an international knowledge review of existing tools and methods for analysing climate change risk, and the report will serve two purposes: Form the basis for producing a scientific article, and serve as the scientific baseline for a number of case-studies aimed at improving an existing method for analysing local impacts of climate change; namely the "Impact Chain" approach.

The partners of UNCHAIN are Western Norway Research Institute (WNRI), Wageningen University & Research (WU), Gesellschaft für Wirtschaftliche Strukturforschung (GWS), Instituto Español de Oceanografía (IEO), Paris-Lodron University Salzburg (PLUS), Nordland Research Institute (NRI), Fraunhofer-Gesellschaft zur Förderung der Angewandten Forschung e.V. (FhG), Stockholm Environment Institute (SEI), Rambøll (Ramboll), and Institut National des Sciences Appliquées de Strasbourg (INSA).

The following authors and partners have taken part in writing this report:

Chapter	Persons (and affiliation)
The impact chain model	Linda Menk (PLUS), Marc Zebisch (Eurac), Stefano Terzi (Eurac), Erich Rome (FhG), Daniel Lückerath (FhG), Mark Meyer (GWS), Stefan Kienberger (PLUS)
User-interface and stakeholder involvement	Elin Leander (SEI), Karin André (SEI), Brigt Dale (NRI), Mari Hanssen Korsbrekke (WNRI), Linda Menk (PLUS), Åsa Gerger Swartling (SEI)
Socio-economic scenarios and societal exposure to climate change	Mark Meyer (GWS), Lisa Becker (GWS), Ulrike Lehr (GWS), Erich Rome (FhG), Daniel Lückerath (FhG), Emmanuel Nyadzi (WU), Ludwig Fulco (WU), Hasse Goosen (WU), Linda Menk (PLUS)
Transboundary climate change impacts	Carlo Aall (WNRI), Katy Harris (SEI), Magnus Benzie (SEI), Mark Meyer (GWS), Marta K. Jansen (WNRI), Nihal Durmaz (INSA), Florence Rudolf (INSA)

This report is the output of the first work package of UNCHAIN, led by Western Norway Research institute (WNRI).

Sogndal, Norway 05.05.2020

Carlo Aall
WNRI, principle investigator of UNCHAIN

Marta Jansen
WNRI, UNCHAIN project coordinator

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Summary

Aim and scope

This report the first deliverable from the project "Unpacking climate impact chains - a new generation of climate change risk assessments" (UNCHAIN). The overall objective of the UNCHAIN project is to improve climate change risk assessment frameworks in order to improve the basis for decision-making and climate change adaptation action. The objective of this report is to further specify the research questions of UNCHAIN presented in the application, in order to ensure that the different cases provide as valuable input as possible to fill the knowledge gaps described in the UNCHAIN application.

The UNCHAIN project take as reference point the concept 'impact chain' (IC), which is an analytical tool that helps to better understand, systemise and prioritise the factors that drive climate impact related risks in a specific system of concern and serve as a backbone for an operational climate risk assessment. The UNCHAIN project will further develop the approach to support climate change adaptation capacity-building, by aiming at five methodological innovations of the current IC approach:

- to develop and test an approach to assess climate change risks that covers both the short-term need for 'adjusting' within the current societal framework and the possible need for long-term and large-scale efforts of 'societal transformation'
- to refine a structured method of co-production of knowledge and integrate this into impact modelling to better account for different views on desirable and equitable climate resilient futures
- to develop and test an applicable framework for analysing how societal change can affect local climate change vulnerabilities, how to conduct an integrated assessment of the combined effect of potential climate and societal changes, and how to better understand the socio-economic consequences involved in local climate change adaptation
- to develop and test a standardized analytical framework for addressing uncertainties involved in local decision-making on climate change adaptation
- to explore the possibility of expanding the logic of impact change along 'time & space', i.e. to include transboundary effects of climate change

Research design

The research design applied in this study has been to review both research and grey literature. This review has been done extensively for two of the chapters (chapter 2 and 3), by adopting a 'systematic review approach' building on principles from systematic review and mapping methods. For the two other chapters, a strategic and more limited selection of literature has been chosen. See more information about the applied method for each chapter.

Knowledge gaps relating to the current application of the Impact Chain framework

Results from UNCHAIN can contribute to further improve the existing IC approach. Key elements are:

- a better integration of quantitative, semi-quantitative, qualitative and narrative approaches

* to consider and compensate the potential bias of the participatory elements within the assessment
* to include future vulnerability conditions based on socio-economic scenarios to better depict future critical conditions
* to address uncertainties and confidence levels for each step in the assessment
* to integrate knowledge from other approaches already existing in literature on the normalization and aggregation phases and the definition of critical thresholds

Particularly for more in-depth and scientific assessments it would be very interesting to forward the IC approach from a 'linear' representation of risk components towards more system dynamics-oriented models.

Knowledge gaps relating to co-producing knowledge on climate change risks

To conclude, like other studies we see a lack of reflection and transparency as regards to stakeholder involvement in knowledge co-production and participatory processes. We also see the need to critically reflect on and be clear about stakeholder roles in the process as well as expected outcomes. This is key to enable better follow-up and comparison between cases which can lead to improvement and enhanced learning. Thus, in the Unchain case studies it will be important to carefully consider how these aspects can be captured throughout the different phases of the project. Moreover, in addition to the specified research question of how knowledge co-production can, in a systematic way best, be integrated in the current Impact Chain framework we also see that the research question specified for this knowledge review – the role of knowledge co-production in climate change risk assessments to better inform decision-making and adaptation action – is still of relevance for the project and should be considered when designing and conducting the case studies.

Knowledge gaps relating to how societal change can affect local climate change risks

While the project tries to contribute to the development of a standardized analytical framework for gaining a better understanding of socioeconomic consequences involved in climate change adaptation, it connects different areas of research. To be able to do so, we must understand the current literature on socioeconomic scenarios and pathways and how they include climate change vulnerabilities, exposure and risks. The scenarios developed under the IPCC reports were scrutinized.

Three important factors have been identified to be crucial in the research for UNCHAIN:

* The element of scale. Climate change damages take place on a local or regional scale and do not respect statistical borders, such as federal states, municipalities or countries.
* The element of addressing risk and uncertainty.
* The relevance of different economic indicators for a science-based climate change adaptation strategy. Here, the fact that decision makers as well as the general public often relate much better to socio-economic indicators, such as GDP, production, costs, or well-being makes economic modelling an indispensable ingredient in the mix used for decision supporting information.

As an opportunity, the project can build upon existing work of its members. A good starting point seems to be the combination of dynamic IO models with the case study work on regionalization of economic and societal consequences.

Knowledge gaps relating to transboundary effects of climate change

Despite the initiation of sophisticated governance structures to manage adaptation at a sub-national, national and international levels of governance, the concept of transboundary climate change risk and the benefits of a scaled approach to adaptation are yet to be widely recognised. The assessments that have taken place have generated few tangible policy recommendations for how to adapt to transboundary climate change risks and even more limited responses and there are significant outstanding questions regarding who 'owns' such risks. This 'blind spot' of climate change adaptation is clearly weakest at the sub-national level of governance.

Specifying the research questions of the UNCHAIN project

Below we have listed the overarching objective and the research innovations of UNCHAIN as they were presented in the application and supplied them with several sub-research questions based on the findings from the extensive literature review presented in this report. The proposed set of sub-research questions will in the following works of UNCHAIN be linked to the cases, in order to secure that all research innovations are sufficiently addressed empirically. This will be done in the succeeding case study protocol.

- Improve climate change risk assessment frameworks aimed at informed decision-making and adaptation action
    - How to identify the relevant system elements and their interrelations when doing impact chain analysis?
    - How to better integrate quantitative, semi-quantitative, qualitative and narrative approaches?
    - How to integrate in the impact chain framework knowledge from other approaches already existing in literature on the normalization and aggregation phases and the definition of critical thresholds?
    - How to forward the impact chain approach from a 'linear' representation of risk components towards more system dynamics-oriented models?
- To cover also the possible need for long-term and large-scale efforts of 'societal transformation'
    - How to link knowledge co-production processes with societal change, and how to evaluate the success of doing so?
- To refine a structured method of co-production of knowledge and integrate this into impact modelling
    - How to design of participatory workshops to be as fruitful as possible?
    - How to critically reflect on and be clear about stakeholder roles in the process as well as expected outcomes when doing impact chain analysis, and how to consider and compensate the potential bias of the participatory elements within the impact chain assessment?

- How to increase the level of reflection and transparency as regards to stakeholder involvement in knowledge co-production and participatory processes?
    - How to best communicate concepts, objectives, possibilities, limitations and results to stakeholders and end users?
    - How can knowledge co-production in climate change risk assessments better inform decision-making and adaptation action?
    - What are the challenges to knowledge co-production in relation to climate change risk assessments, such as stakeholder representation, scale and scope of projects in relation to decision-making contexts, differing perspectives and understandings of the problem definition, communication, and legitimacy of the climate information?
    - What are the promotors of knowledge co-production in relation to climate change risk assessments, such as the role of knowledge brokers and intermediaries, the use of interactive models and scenarios, the stakeholder group composition, and the validation of model and the extant that this will increase the legitimacy of the information that goes into the adaptation planning processes?
    - What are the critical factors concerning how knowledge co-production processes can lead to changes in actual adaptation action, such as collaboration between public bodies and academia, and take into consideration that stakeholders at different ends of the 'adaptation learning cycle' have different needs and capacities to engage in participatory processes?
- To develop and test an applicable framework for analysing how societal change can affect local climate change vulnerabilities
    - How to include future vulnerability conditions based on socio-economic scenarios to better depict future critical conditions?
    - How to gain a better understanding of socioeconomic consequences involved in climate change adaptation?
    - How to combine the differences in scale between where statistical data is produced (within administrative borders at national, county or municipal levels) and where the impacts of climate change manifests itself (mostly independent of administrative borders)?
    - What are the most relevant economic indicators to include in impact chain assessments?
- To develop and test a standardized analytical framework for addressing uncertainties involved in local decision-making on climate change adaptation.
    - How to better address uncertainties and confidence levels for each step in the impact chain assessment?
    - How to overcome the problems of deep uncertainty about future climatic and socio-economic conditions, as well as the lack of data – even of present conditions – when doing risk assessments?
    - How to address uncertainties related to the socioeconomic aspects involved in impact chain assessments?
- To include the trans-national impacts of climate change and to link mitigation and adaptation in climate risk and vulnerability assessments

- What are the most important transboundary climate change risk in the involved countries?
- How can different levels of governance identify and then adapt to transboundary climate change risks?
- Who (private/public actors, at different levels and within different sectors) are most accountable for managing different sub-categories of transboundary climate change risks?
- What are the most important factors that limit the capabilities of policymakers to address transboundary climate change risks?
- How to articulate and frame transboundary climate change risks so it will increase the motivation of identified and targeted policymakers to respond to such risks?

Introduction

This report the **first deliverable** from the project "Unpacking climate impact chains - a new generation of climate change risk assessments" (UNCHAIN). The overall **objective** of the **UNCHAIN project** is to improve climate change risk assessment frameworks in order to improve the basis for decision-making and climate change adaptation action. The objective of this **report** is to further specify the research objectives and innovations of UNCHAIN presented in the application, in order to ensure that the different cases provide as valuable input as possible to fill the knowledge gaps described in the UNCHAIN application.

UNCHAIN's **scientific** objectives are to (1) contribute to accurate, science-based, high resolution and context specific climate change risk assessments (2) improve methods to assess impacts of climate change on the economy and society (3) apply the concept of co-production of knowledge in all stages of knowledge development, and (4) investigate how future scenarios can be made more comprehensive by combining societal exposure and vulnerability projections with climate projections and impact models, yielding a novel combination of a quantitative and qualitative risk assessment approach. The UNCHAIN project take as reference point the concept 'impact chain' (cf. figure below).

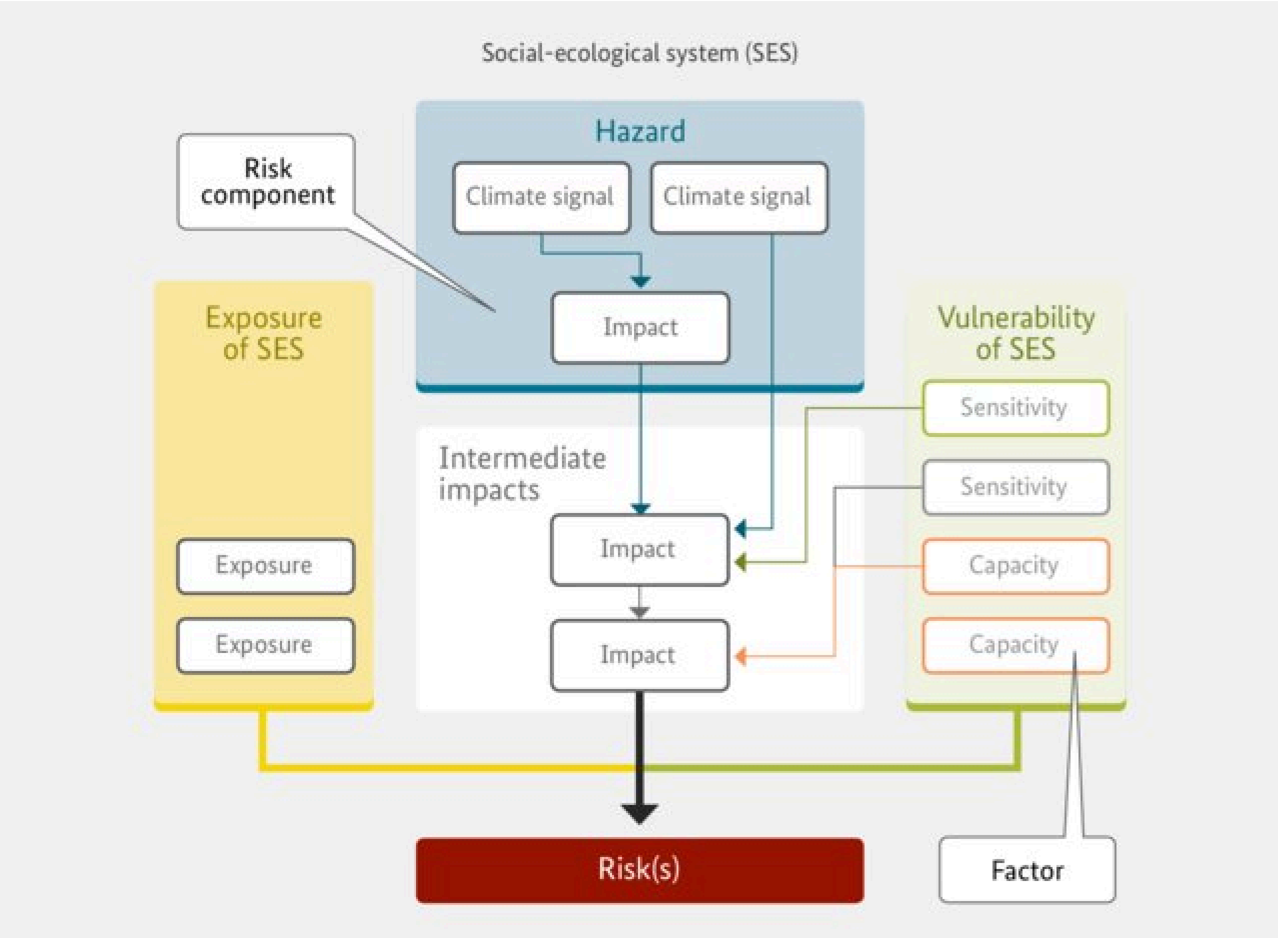


Figure 1 *The Impact Chain approach (Zebisch et al, 2017)*

Impact Chains (ICs) is an analytical tool that helps to better understand, systemise and prioritise the factors that drive climate impact related risks in a specific system of concern and serve as a backbone for an operational climate risk assessment. The concept was developed by EURAC Research for studies on climate vulnerability in the Alps (Schneiderbauer et al, 2013) and further developed for the national climate vulnerability assessment for Germany (Buth et al, 2017) and the GIZ Vulnerability Sourcebook on climate vulnerability assessment in the context of international cooperation (Fritzsche et al, 2014). The concept has also been adapted to the new IPCC Assessment Report (AR)5 concept of climate risk (Zebisch et al, 2017) and recommended for climate risk assessments in the context of Ecosystem Based Adaptation (Hagenlocher et al, 2018). ICs have since then been more and more widely used as a climate risk assessment method. The method is perceived as a useful tool for analysis as well as for communication of complex cause-effect relationships in climate change impacts and risks.

Impact chains are foremost a conceptual model for a specific climate risk, composed of risk components according to the IPCC Assessment Report (AR)5 concept (hazard, exposure, vulnerability) and underlying factors for each of these components (cf. figure 1). The structure of the impact chain represents the main cause effect chains: a climate signal (e.g. a heavy rain event) may lead to a sequence of intermediate impacts (e.g. erosion upstream that contributes to flooding downstream), which in interaction with the vulnerability of exposed elements of the social-ecological system finally lead to a risk (or multiple risks). For an operational risk assessment, impact chains serve as a basis for the selection of appropriate indicators as well as a backbone for the aggregation of indicators to composite risk indicators. Operational assessments based on impact chains can combine data and model driven approaches with expert-based approaches. Participatory methods (to be conducted in e.g. workshops) are implemented at all steps, to validate the results and ensure ownership and sustainability. ICs increase the usability of climate projections, climate impact models as well as the integration of social, economic and institutional drivers, articulating their results and formatting them in a more understandable format. ICs have the capacity to be inclusive, open and cross sectoral and cross scale and allow to identify and aggregate, downscale risks, and compare sectors.

At the core of UNCHAIN are several **cases** conducted in each of the involved countries, as well as in developing countries (i.e. concerned by cooperation projects). The objectives of the case studies are: (1) To develop in dialogue with local stakeholders and subsequently test changes and alterations of the current impact chain model for risk assessments; (2) to evaluate the effect of this model with respect to creating a more resilient and climate robust society; and (3), ensure that the project encounters as many of the multiple ways in which climate change, climate change policies and its impacts influence individual and collective adaptation measures as possible, including the effects of climate impacts across space (transnational climate impact exposure). The case studies are ‘local’ in the sense that they involve stakeholders involved in ‘real’ decision-making processes on how to adapt society to climate change. The case studies differ in scope. They are multi-method in the sense that they combine quantitative modelling and qualitative methods such as document analysis, interviews and workshop techniques (e.g Gerger Swartling et al, 2019). They also involve all partners: experts on economics simulate the “hard” economic indicators and conduct analyses for case studies in some countries, climate modelling analyses risks across several cases and the results are used as illustration material for the bottom-up approaches (i.e. for initial discussions with stakeholders).

The IC approach has been well-received by different organizations partly due to its ability to bring context-specific information into the risk assessment. The UNCHAIN project will further develop the approach to support climate change adaptation capacity-building, by aiming at **five methodological innovations** of the current IC approach.

The **first** innovation of UNCHAIN is to develop and test an approach to assess climate change risks that covers both the short-term need for 'adjusting' within the current societal framework and the possible need for long-term and large-scale efforts of **'societal transformation'**, in which the latter relates to "(t)he altering of fundamental attributes of a system (including value systems; regulatory, legislative, or bureaucratic regimes; financial institutions; and technological or biological systems)" (IPCC, 2012:4).

The **second** innovation of UNCHAIN is to refine a structured method of **co-production of knowledge** and integrate this into impact modelling to better account for different views on desirable and equitable climate resilient futures. This will also allow development of user-oriented, decision-driven Climate Services that support the goal of actionable knowledge (Gerger Swartling et al, 2019, André et al, 2020). In this project we recognize the definition of climate services as put forward by the Global Framework for Climate Services (GFCS) as "providing climate information in a way that assists decision-making by individuals and organizations" (WMO 2014: 2).

By now, it is well established that knowledge to inform climate change adaptation needs to go beyond projections from deterministic or probabilistic climate models (e.g. CMIP5, CORDEX), and must include also scenarios for social, economic and political development (Moss et al, 2010). However, it has proven challenging to implement such approaches in the real world. Thus, the **third** innovation of UNCHAIN is to develop and test an applicable framework for analysing how **societal change** can affect local climate change vulnerabilities, how to conduct an integrated assessment of the combined effect of potential climate and societal changes, and how to better understand the socio-economic consequences involved in local climate change adaptation.

Schneider and Kuntz-Duriseti (2002) suggest that climate policymaking can address climate-related uncertainties by attempting to reduce uncertainty, through supporting more data collection, research, modelling, simulation etc. However, the daunting uncertainty surrounding climate change, the speed at which the climate is changing, and the need to make decisions well before uncertainty is better addressed, lead to the claim to manage uncertainty rather than master it, by means of integrating uncertainty into policymaking. Thus, the **fourth** innovation of UNCHAIN is to develop and test a standardized analytical framework for addressing **uncertainties** involved in local decision-making on climate change adaptation.

The **fifth** innovation of UNCHAIN explores the possibility of expanding the logic of impact change along 'time & space'. A limited number of studies, mostly addressing the national level, have pointed out that, in high-consuming countries with an open economy, the **transboundary effects** of climate change can be more challenging than the local ones (Benzie et al, 2016; Hedlund et al, 2017). The ambition in the UNCHAIN project is to assess how impacts of climate change can transcend country borders mediated by means of societal change to produce or exacerbate local vulnerabilities. Exposure to transnational climate impacts in future will depend to a high degree on the shape and nature of future socio-economic development, meaning there is also a need to consider future variables such as trade openness, financial investment, supply chains, migration and globalization when assessing future climate vulnerability in Europe (Benzie et al, 2017).

The **research design** applied in this study has been to review both research and grey literature. This review has been done extensively for two of the chapters (chapter 2 and 3), by adopting a 'systematic review approach' (Dawkins et al., 2019) building on principles from systematic review and mapping methods (Haddaway, Woodcock, Macura, & Collins, 2015). For the two other chapters, a strategic and more limited selection of literature has been chosen. See more information about the applied method for each chapter.

The impact chain model

Introduction

The (quantified) Sourcebook approach (cf. Fritzsche et al., 2014) always starts with a scoping phase to understand the context and the assessment requirements, followed by the *impact chains* development and a third, highly participative phase, where indicators suitable for quantifications are selected. Following operational phases include data processing, weighing of indicators and their aggregation into risk components, and final aggregation of risk components into an overall risk assessment. While such an approach has been widely applied, no systematic reviews of alternative and parallel evolving approaches has yet been carried out.

This chapter aims at closing this gap by identifying and reviewing *impact chain* related approaches. Thus, this chapter gives an overview of the past development, implementation and identified knowledge-gaps and key challenges of *impact chains* and related methods utilized to describe and capture complex interrelated phenomena in the context of climate change risk assessments. The review will primarily contribute to giving an overview of the basis from which onward the five innovations to the Climate Change Risk Assessment (CCRA) framework can be developed. Furthermore, the review serves to refine and improve the process of generating *impact chains*. Consequently, the review of international research including academic and grey literature will explore the role of the impact chain development process in climate change risk assessments to better inform decision-making and climate change adaptation action. Through the review we will address the following **questions**:

- How have impact chains and related methods been applied in previous studies? (e.g. participatory, modelling, etc.)
- What knowledge-gaps and challenges were identified?
- Have suggestions been made which could possibly improve the impact chain development process? (e.g. to better include qualitative/narrative and quantitative/system-dynamics approaches into the impact chain model?)

Method

The review in this chapter was conducted by adopting a 'systematic review approach' adapted from Dawkins et al. (2019 p. 1453):

1) **A method plan**: outlining the review questions to be addressed, parameters and criteria for selection, searches, screening and synthesis process in a protocol;
2) **Search strategy**: using multiple databases with carefully designed search strings to increase comprehensiveness and avoid bias in document inclusion;
3) **Screening against criteria**: screening all search results using pre-defined inclusion criteria, documented in the method for transparency and repeatability;
4) **Screening cross-check**: title and abstract screening was conducted by one reviewer but with several meetings during the process with second reviewer to check for consistency.
5) **Coding selected documents**: coding, describing and synthesizing the documents in a transparent and consistent manner, using a standard coding form;

6) **Describing the process**: providing a detailed description of the method and full supplementary information to ensure transparency and repeatability.

The protocol was shared and discussed by the PLUS research team and UNCHAIN partners: Eurac research, FhG and GWS. Two main concepts were determined for the search: impact chains and related concepts, and climate change risk assessment. To create a search string of these concepts, a list of all possible synonyms was identified. This happened based on authors' previous experience and by checking different terms used in a selection of articles.

In total, 234 articles were identified by applying the search strings to the **Scopus** and **Web of Knowledge** databases. Each articles' abstract and title was then screened by two reviewers, who were given the options to label each article as either "fitting" (Yes), "probably fitting" (Maybe) or "not fitting" (No), based on previously agreed upon inclusion criteria (see table below). The table below shows the results of the screening exercise.

Table 1 *Decisions made by the reviewers after reading the articles' abstracts*

Review decision	Count	Review decision	Count
No/Maybe	26	Yes/Maybe	26
No/No	111	Yes/No	21
Maybe/Maybe	27	Yes/Yes	23
Grand Total: 234			

The 23 articles voted as "fitting" (resp. Yes/Yes) by both reviewers, as well as the 26 articles voted "fitting" by one and "probably fitting" (resp. Yes/Perhaps) by the other reviewer were then retrieved as full-text versions and prepared for the coding exercise. Six of these 49 texts could not be located and were therefore neglected. The remaining 43 articles were read and coded according to a previously defined coding-scheme (see Annex).

If the reviewer, while reading the full text, figured that the article was not fitting after all, it could still be excluded from the coding exercise. This has happened 11 times. The reason for the exclusion, e.g. 'review article', was then noted down in the column 'exclude?'. However, seven additional articles were added, that were not in the result list of Scopus and Web of Knowledge, but were known to the authors. This leaves a total of 39 coded articles. The following part summarizes the main findings. Figure 2 shows the stepwise narrowing of literature.

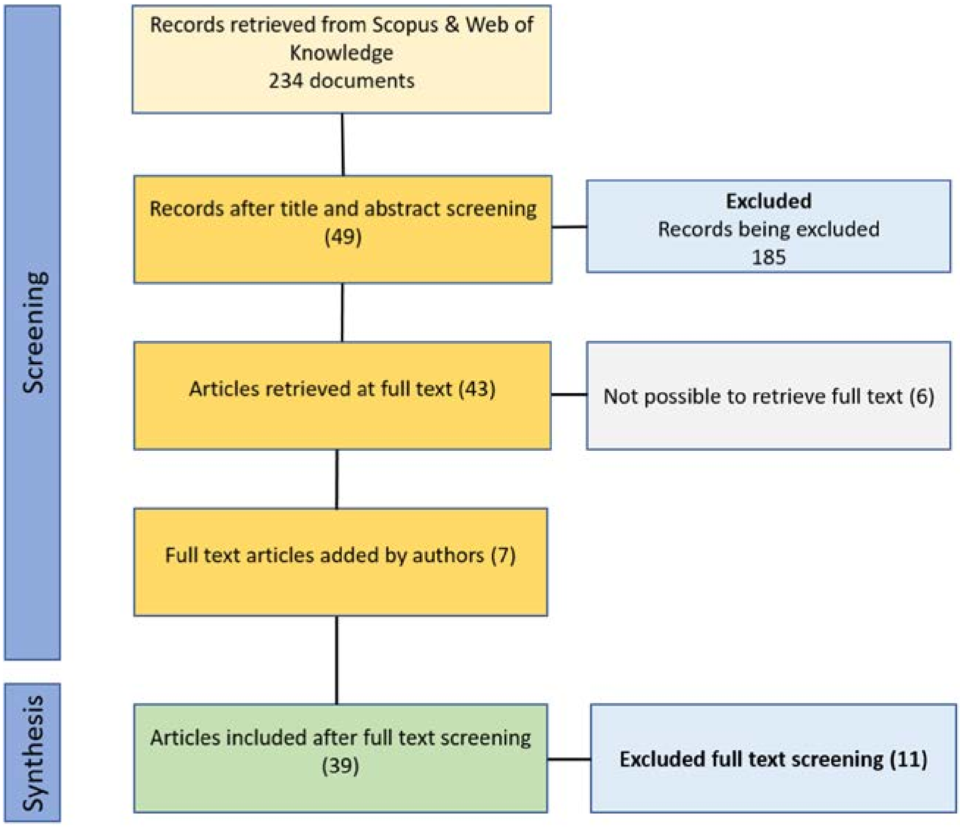


***Figure 2** The applied stepwise narrowing of relevant literature, adapted from Haddaway et al. (2017)*

Objective of this chapter was to identify difficulties and knowledge-gaps related to the modelling of climate change impact chains or similar approaches utilized as tools for climate change risks assessments. To achieve this, a selection of 39 articles was reviewed and information was selectively extracted. This information partly concerns the general setting of the studies, as well as the methods used and the reflections about the process or outcome. The first part of the following literature review evaluation summarizes the results on the topics "general settings" and "methods used". This part is held rather short and results are mainly displayed as charts. The second part of the evaluation describes the results on "challenges and knowledge gaps". As these results are at the core of this work, they are described in a detailed flow text.

The figure below shows the **geographical** distribution of the studies. Approximately half of them relate to a European country, with UK standing out.

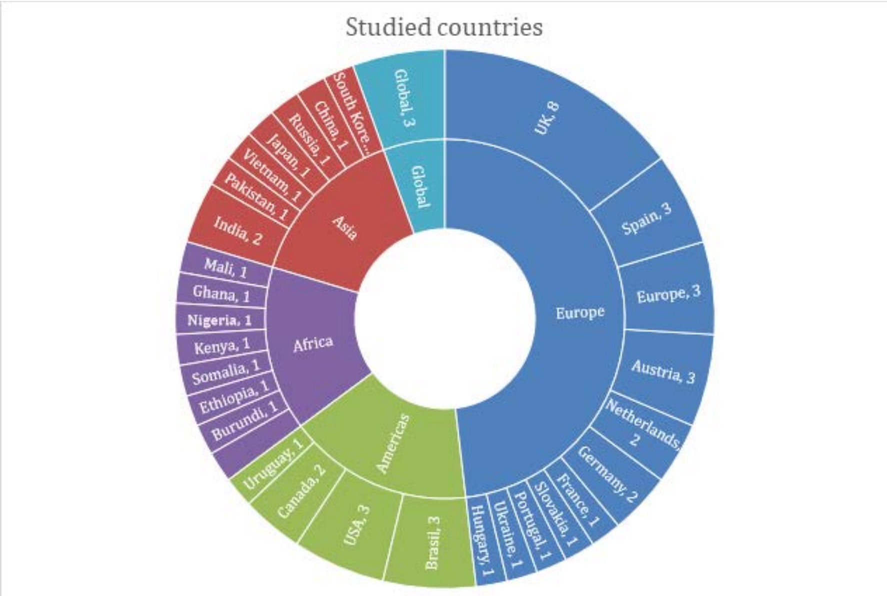


Figure 3 *Geographic distribution of the analysed studies*

Two thirds of the studies do not assess risk at the **national** level, but act on more local levels or even individual elements of critical infrastructure (e.g. Fluixá-Sanmartín, Morales-Torres, Escuder-Bueno, and Paredes-Arquiola (2019) dealt with the Santa Teresa dam in Spain and the impact of climate change on its failure risk). The remaining 13 studies deal with climate change risk at the national, interstate or even global level.

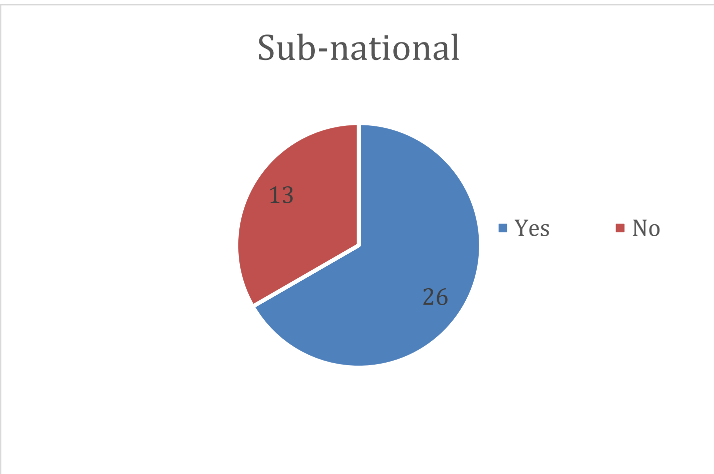


Figure 4 *The number of studies acting on a sub-national level vs. those that act on national, international or global level*

The presentation of analysed **hazards** turns out to be rather complicated, as what is stated as 'the problematic factor' in the studies varies between hazards and intermediate climate impacts and different levels of hierarchy. The table below displays the number of times each hazard or impact has been mentioned. The table attempts to bring structure to the hazards/impacts mentioned by the authors. A lack of consistency can be identified, since the naming includes almost all possible hierarchical levels on which a hazard or impact can be described.

Table 2 *The number of times each hazard/impact has been dealt with in the studies analysed*

<table>
<tr><td colspan="2"></td><td>Hazard</td><td>Climate change impact</td></tr>
<tr><td rowspan="4">Changed temperature patterns (2)</td><td rowspan="2">Rapid onset events (1)</td><td colspan="2">Heatwave (7)</td></tr>
<tr><td colspan="2">Cold spell (2)</td></tr>
<tr><td rowspan="2">Slow onset events</td><td rowspan="2">Sea Level Rise (2)</td><td>Coastal erosion (2)</td></tr>
<tr><td>Storm surges (1)</td></tr>
<tr><td rowspan="6">Changed precipitation patterns (2)</td><td rowspan="6">Rapid onset events (1)</td><td rowspan="2">Storm/wind, heavy precipitation/snow (9)</td><td>(Coastal) floods (17)</td></tr>
<tr><td>(Coastal) erosion/landslide (6)</td></tr>
<tr><td rowspan="4">Drought (11)</td><td>Water scarcity (2)</td></tr>
<tr><td>Water quality deterioration (1)</td></tr>
<tr><td>Salinization (1)</td></tr>
<tr><td>Desertification/forest dieback (2)</td></tr>
<tr><td colspan="4">Overarching without further specification (9)</td></tr>
</table>

Almost half of the studies made use of the definitions given by the 4th and 5th IPCC Assessment Reports of the Working Group II (WGSII) (Figure 3). The IPCC AR4 however, does not refer to **risk** but **vulnerability** as the factor at the end of the equation. They describe vulnerability as being "a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity" (Parry et al., 2007). In the AR5, the risk concept has been adopted from the disaster risk reduction (DRR) community, describing risk as the interaction of vulnerability, exposure and hazard (Field, 2014). Over a third of the studies do not mention any specific risk concept, while six studies refer to either own risk concepts or concepts used in other domains.

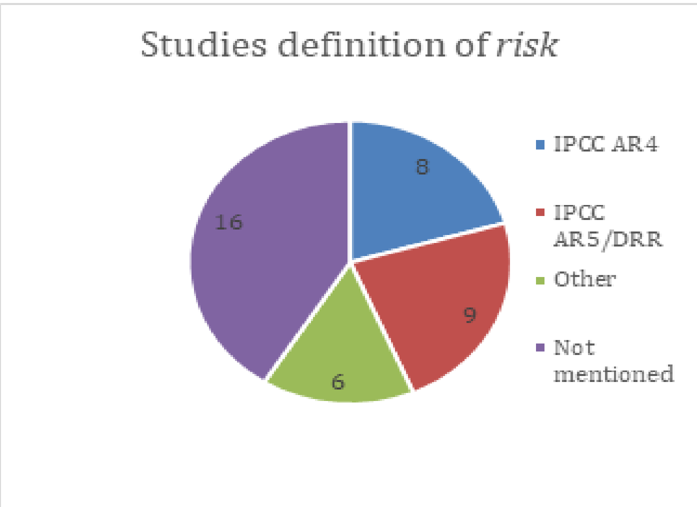


Figure 5 *The number of studies using different concepts of risk/vulnerability*

Climate risk analysing methods

What all analysed texts had in common was that some sort of climate change risk assessment has been carried out. The analysis gave, that the range of approaches towards this issue is broad and diverse, ranging from economic quantifications, impact chain modelling and Network Analysis to System Dynamics Models, Causal Loop Diagrams, Topological Networks or Fuzzy Cognitive Maps. This is already an interesting finding, as it illustrates that Climate Change Risk Assessments are gaining relevance in a wide range of specialized fields and that these field are approaching risk from their own point of view and an own set of methods. This could be indicative for the absence of a reliable, uniform approach. The figure below shows the distribution of **modelling** approaches. When speaking of impact chains, it does not necessarily refer to the concept of *impact chains* defined in the *Vulnerability Sourcebook*, but impact chains in a wider sense.

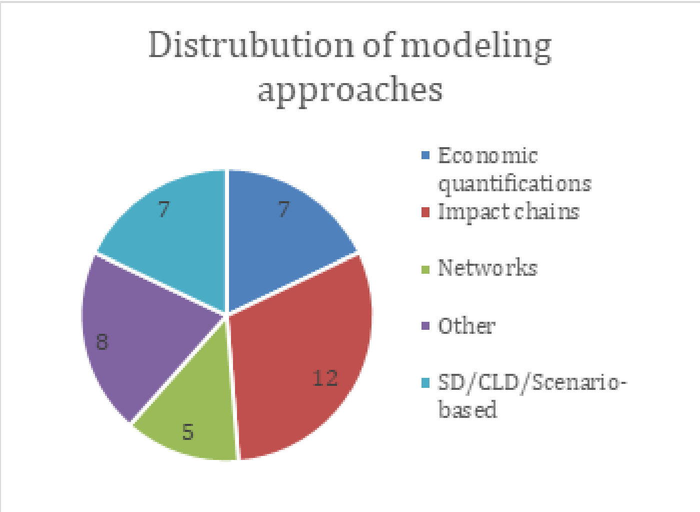


Figure 6 *The occurrence of different model types*

The following examples serve to provide an insight into the variety of methods found in the assessed studies.

<u>Impact Chains</u>

Some studies aimed at developing specific climate change *impact chains* as described in the *Vulnerability Sourcebook*, through a combination of participatory workshops with experts and stakeholders, underpinned by information derived from existing literature, models or other available sources (e.g. Becker, Renner, & Schneiderbauer, 2014; Greiving et al., 2015; Hussain, 2014; Kabisch et al., 2014; Kienberger, Borderon, Bollin, & Jell, 2016; Lückerath et al., 2018; Rome et al., 2019; Rome et al., 2018).

Wahab and Ludin (2018) interestingly borrowed the exact *impact chain* for flood vulnerability presented as an example in the *Vulnerability Sourcebook* and used it as input for an Artificial Neural Network to successfully estimate flood vulnerability in Malaysia.

Others used the term *impact chain* but tended to refer to them as a concatenation of system element that result from logical conclusions. These studies did not have the development process of *impact chains* in the focus or as an important intermediate goal, but rather considered them as given or self-evident, to be used as input for e.g. Computable General Equilibrium models (Steininger, Bednar-Friedl, Formayer, & König, 2016) or Bayesian Network Analysis (Moglia, Nguyen, Neumann, Cook, & Nguyen, 2013).

Networks

Kang and Park (2018) for example, aimed to identify trends in climate change risk indicators by using network analysis fed by text mining results from 3098 South Korean national and regional newspaper articles related to climate change, published over a course of 24 years. With the results, they want to provide policy response and urban planning implications that can reduce climate change risk in South Korea. Similarly, Debortoli, Sayles, Clark, and Ford (2018) used network analysis fed by information extracted from literature to assess the vulnerability of Inuit Communities in the Canadian Arctic. Pant, Hall, and Blainey (2016) established a framework for national analysis of vulnerability of interdependent infrastructure in the United Kingdom, by using interdependent network representations of key critical components and their interactions at local and national scales.

Monetary quantifications

Those studies focused at expressing risk in monetary terms preferably used Computable General Equilibrium (CGE) models. Steininger et al. (2016) for example, used a CGE model containing all economic impact fields of all climate change hazards in Austria and determined the six impact field which will be responsible of the lion's share of macroeconomic effects of climate change in Austria by 2050. Moreover, Koks et al. (2019) used a multi-region CGE, soft-linked with hydrological model projections of future flood events to assess the indirect economic effects caused by individual flooding events in other regions via supply chains.

Thacker, Kelly, Pant, and Hall (2018) used a different technique, also widely used in economic modelling, which is input-output modelling or cost-benefit analysis to evaluate the benefits of investment in adaptation of interdependent critical infrastructure to reduce hydrometeorological risks.

Others

About half of the studies used other techniques, like System Dynamic (SD) models, e.g. derived from different sources like expert judgement and climate projections to measure system performance during a possible disaster scenario (Tonmoy & El-Zein, 2013). Or a SD model coupled with a hydrologic model to support the development of drought adaptation policies at the Horn of Africa (Gies, Agusdinata, & Merwade, 2014).

Apan and McDougall (2015) generated a topological network of interconnected infrastructure networks in Australia to characterize the Critical Infrastructure Systems' (CISs) interdependencies and exposure to fluvial flooding, to outline climate adaptation and flood mitigation measures. Romero-Lankao and Norton (2018) developed in collaboration with stakeholders, so-called Fuzzy Cognitive Maps (FCMs) which are, like *impact chains* or Causal Loop Diagrams, a technique for representation and acquisition of causal knowledge. They used this technique to analyse the interdependencies which mediate the cascading negative consequences on people of Food-Energy-Water Systems triggered by flooding events in Boulder, USA.

Knowledge acquisition

The two figures below refer to the methods/means used for knowledge acquisition. The three major methods (1) literature review, (2) participatory workshops/expert consultations, and (3) statistical data analysis and the usage of existing models are almost evenly distributed. Yet, more than half of the studies were not limited to just one strategy but used a mixture instead. While some studies are solely based on (systematic) literature reviews, others might have used a mixed approach without specifically mentioning it (e.g. it can be assumed that some studies were preceded by some sort of literature review, without explicitly mentioning this).

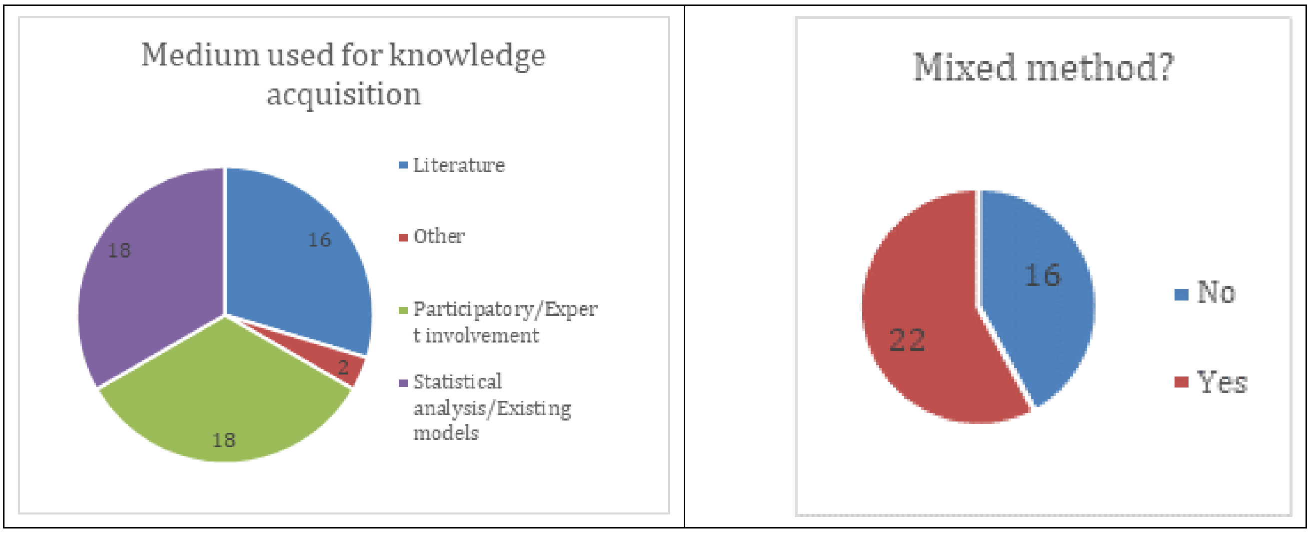


Figure 7 *The distribution of methods used for knowledge acquisition (left) and the extent if more than one method was used (right)*

Challenges and knowledge gaps

The assessed challenges and knowledge-gaps can be grouped broadly into five categories:

- Model design
- System elements and interrelations
- Data availability and reliability
- Selective perspectives, biases or lack of better knowledge and experiences
- Keeping it clear and transparent

The established categories are discussed in more detail below.

Challenges related to model design

Most mentioned challenges and knowledge-gaps relate to the used model design itself. Those studies which attempt to quantify possible future monetary losses (or savings due to adaptation measures), report the common shortcoming that the model is **likely to underestimate the numbers.** This is due to a **lack of strategies to quantify indirect impacts** (Koks et al., 2019) and **factors of non-monetary value** (Thacker et al., 2018). Losses caused by negative impacts on **biodiversity** and the **impairment of ecosystem-services** are particularly intangible (Lapola et al., 2018; Schwarze, 2015). While these quantifications are likely to underestimate future costs, *impact chains* **do not offer model-based quantification methods at all** (Steininger et al., 2016) which makes it difficult to convince policy makers to provide funding for adaptation projects (Hussain, 2014). Also pointed out are the lacking methods for modelling pathways for **future development of exposure** – e.g. in Rome et al. (2019) with regards to the development of urban areas and populations - and "long-term demographic and socio-economic scenarios, as well as considerations of intersectoral interactions" (Schwarze, 2015). Some studies conclude that the used model design has not been a suitable choice to **capture some of the targeted changes and effects** (Bachner, Bednar-Friedl, Nabernegg, & Steininger, 2015; Distefano, Riccaboni, & Marin, 2018; Hedlund, Fick, Carlsen, & Benzie, 2018; Koks et al., 2019). Others see their results somewhat limited by the **inherent uncertainties** given by the dispersion of climate projection inputs and the sensitivity of some modelled aspects (Anandhi, Sharma, & Sylvester, 2018; Fluixá-Sanmartín et al., 2019) or by the lack of knowledge about the most reliable time-step for each individual system (Gies et al., 2014).

Challenges related to the identification of system elements and interrelations

A challenge frequently mentioned relates to the **identification of (relevant) system elements and their respective interrelations**, particularly due to their inherent complexities and range of subjects (Greiving et al., 2015; Olabisi et al., 2018). For Steininger et al. (2016) insufficient knowledge of certain impact fields resulted in the exclusion from their macroeconomic model, despite the knowledge of their importance. Others mention difficulties in **managing interdependencies** between climate change risks (Dawson, 2015), drawing clear causal links between climate signal and impact (Kabisch et al., 2014), linking the complexity of climate change causal chains to actual risk to the investigated asset (Dikanski, Hagen-Zanker, Imam, & Avery, 2016) or to capture adaptive- and coping-capacities at municipality resolution (Lissner, Holsten, Walther, & Kropp, 2012). According to Steininger et al. (2016) these shortcomings are caused, inter alia, by a lack of available researchers specialized in the respective impact fields "who can specify *impact chains* and develop and apply the respective impact models".

Usually, *impact chains* are developed and implemented despite the knowledge about their imperfections. Yet, when the analyst is at the stage of verification, it **lacks methods to evaluate the results for their correctness** (Becker et al., 2014), due to lacking necessary evaluation schemes (Hussain, 2014) and even lacking evaluations of past (economic) impacts caused by climate events/disasters. This hold especially true for the validation of indirect costs, as they are "proven to be difficult as the wider economic impacts after a disaster are not well documented (Dottori et al., 2018) and, for Europe, are lacking almost completely" (Koks et al., 2019).

Challenges related to data availability and reliability

Another big bottleneck in climate change risk assessments is the **availability of reliable data** (Becker et al., 2014; Debortoli et al., 2018; Gies et al., 2014). Especially when the risk assessment is aimed to be spatially-explicit, the heterogeneity and spatial scale of available data (Becker et al., 2014), collection and assembly of high-resolution, national-scale data (Thacker et al., 2018), mismatching spatial resolutions of studies in meta-analysis and resolutions required for impact assessments (Anandhi et al., 2018) and barriers on higher governance levels (Rome et al., 2019) may complicate and limit the quality of the assessment. This leads to the shortcoming, that aspects which can't be captured are neglected in a spatial assessment, albeit being integral system elements which should be presented (Kienberger et al., 2016). More detailed limitations include the **inability to train**

Bayesian networks in a statistical manner due to a lack of sufficient datasets (Moglia et al., 2013). Moreover, the **inability to use historical weather records** to estimate trigger events and probabilities (as not enough of these events had happened in the past) (Dikanski et al., 2016) and the **inability to make assessments and results comparable** (between cities) as comparable information, e.g. on existing adaptation measures, is not available (Tsavdaroglou, Al-Jibouri, Bles, & Halman, 2018).

<u>Challenges related to selective perspectives, biases or lack of better knowledge and experiences</u>

Those studies which included some sort of participative process report that involved stakeholders tended to understand the assessed situations from **perspectives of their own disparate knowledge and experience** (Greiving et al., 2015; Moglia et al., 2013) and were primarily focused on **only their system of interest, rather than the larger, interconnected system** (Romero-Lankao & Norton, 2018). Another challenge mentioned concerns the **validity of the expert judgement**, as it is inherently subjective (1) and knowledge might be limited due to limited past experiences to draw conclusions from (2) (Tsavdaroglou et al., 2018). Tsavdaroglou et al. (2018) additionally raise the issue that in their study none of the stakeholders had the **"bigger picture" in mind**, which caused a lot of coordination and data collection. Due to these reasons, it is important to double-check if the group of stakeholders covers all relevant perspectives (Greiving et al., 2015). Kang and Park (2018) used a text mining approach to identify trends in climate change risks from Korean climate change related newspaper articles while Debortoli et al. (2018) conducted a network analysis based on a systematic literature review to assess vulnerability of Inuit communities in the Canadian Arctic. Both teams of authors concluded that their results are **biased** by the analysed medium (i.e. newspaper articles and scientific literature) and point to the usefulness of **elaborating the results with expert opinions**.

<u>Challenges related to keeping it clear and transparent</u>

The challenges mentioned in this category are partly related to the **complexity of the methodological framework** covering the subject and the number of **terms and concepts** associated with it, some of them being unintuitive when newly introduced to stakeholders (Kienberger et al., 2016). Moreover, Greiving et al. (2015) raise the issue that terms might be unclear to stakeholders, as they are used differently in different disciplines, e.g. the understanding of risk and vulnerability in the DRR community vs. IPCC community prior to the IPCC AR5. The other part of mentioned challenges relates to the difficulty **to combine a multitude of information and still manage to present them in a clear and concise manner** (Becker et al., 2014), e.g. depicting all sector-specific relationships in a single figure (Yokohata et al., 2019). Kabisch et al. (2014) point out that, in order to keep *impact chains* manageable, not all interrelations can be included.

Opportunities and recommendations

The assessed opportunities and recommendations can be grouped broadly into four categories:

- Combining quantitative data and expert judgements
- Model enhancement
- Visualizing results
- Finding out what favors vulnerability

The established categories are discussed in more detail below.

Opportunities and recommendations related to the combination of quantitative data and expert judgements

Many studies have mentioned the benefits **of combining quantitative information with expert judgements or stakeholder participation**. Hussain (2014) considers the specific **know-how and varying perspectives** of stakeholders as invaluable assets. Studies that have not yet integrated expert participation in their results mention that this would have had the potential to further improve their results (Debortoli et al., 2018), e.g. by reducing uncertainties (Kang & Park, 2018). But what potentially plays an even greater role in terms of stakeholder involvement is the resulting **legitimacy of the results** (e.g. Kienberger et al., 2016). Kabisch et al. (2014) describe the combination of stakeholder involvement and quantitative data as beneficial, as the involved communities found their **own perspectives reflected** in the *impact chains*, which supported joint discussions. Stakeholder participation is further described by Lozoya et al. (2015) as an important condition for **successful management, improved equitability and transparency**. When it comes to taking results into action, increased legitimacy of results is described as naturally **lowering the barrier between research output and implementing (adaptation) measurements** (Greiving et al., 2015). Moglia et al. (2013) second this by reporting that developing e.g. the spatial representation of the developed knowledge base in the form of a map book resulted **in easier adoption of outcomes** by local water planners. In terms of a good communication between researchers and stakeholders Kienberger et al. (2016) point out the importance of communicating limitations. Furthermore stressed is the need to **establish a set of common terms, definitions and objectives** which can be communicated to the stakeholders, e.g. to distinguish between direct and indirect impacts (Kabisch et al., 2014) or to clearly demarcate the system of interest and the policy questions to be addressed. In general, **stakeholder participatio**n through, e.g. exercises that seek to spark learning, are perceived as a **good means** for addressing future challenges and to be prepared for the impacts of future extremes (Romero-Lankao & Norton, 2018).

Opportunities and recommendations related to model enhancement

Several studies mention, that the **inclusion of more or better scenarios** would potentially have had a positive impact on the results of their risk assessment. The need for improved scenario implementation ranges from introducing **further climate scenarios** (Lissner et al., 2012) to **socio-economic, land use and demographic scenarios** (Steininger et al., 2016). Steininger et al. (2016) further suggest to not only focus on a selection of key climate sensitive sectors, as, according to them, this makes an assessment inherently incomprehensive. Thacker et al. (2018) who evaluated the benefits of investments in the adaptation of interdependent critical infrastructure, see benefits in the inclusion of time-varying probabilistic hazard-data and a more comprehensive evaluation and **attribution of costs**. Possible opportunities related to the **inclusion of geographical data** are seen by Debortoli et al. (2018), while Becker et al. (2014) recognizes Geographical Information Systems (**GIS**) as a valuable participatory instrument for the discussion of different vulnerability factors or suitable indicators, or as a platform for the visualization and monitoring of vulnerability results. To summarize, using **robust methods, applying appropriate modelling tools and integrating valid data** will increase the overall validity of the model and the corresponding results (Dawson, 2015; Gies et al., 2014; Kienberger et al., 2016). **Other plans** to enhance future modelling results include (1) allowing for the prioritization of adaptation investments using ranked impacts (Thacker et al., 2018), (2) enhancing robustness by enabling cross-sample comparisons through the definition of stable benchmarks (Tapia et al., 2017), or (3) implementing agent-based gaming within a System Dynamics model to e.g. portray decisions and conflicts of interest (Gies et al., 2014).

Opportunities and recommendations related to visualizing results

The visualization of results has been mentioned as playing an important role in several respects, e.g. as a **guide for stakeholders** to prepare for possible future impacts related to their field of activity or for **understanding the bigger picture** (Yokohata et al., 2019). Yokohata et al. (2019) furthermore found that illustrating the course of cascading risks by its layered structure of natural, socio-economic and human systems can effectively convey the overall picture of climate risks. The visual representations of *impact chains*, as described in the *Vulnerability Sourcebook*, are being valued as an important result on its own, as they present an **understandable conceptual model of all identified relationships** and **enable adaptation planning and awareness raising** (Hussain, 2014).

Opportunities and recommendations related to finding out what favours vulnerability

Understanding vulnerability, how its components are interrelated and how it might develop in the future is one of the key elements of every (human-cantered) climate change risk assessment. Lissner et al. (2012) therefore suggest carrying out detailed examinations of local and regional vulnerability and to integrate individual risk factors of sensitive population groups to better characterize population vulnerability. The evidence basis for a more detailed characterization of (urban) vulnerability can, according to Tapia et al. (2017) be achieved by **focusing on adaptation measures which are already in practice**. **Narrative examples** of risk/vulnerability interconnections **from the past** (e.g. food security and conflict) can promote understanding for the linkages between climate risks, which in turn provides better understanding of a particular risk (Yokohata et al., 2019). Dawson (2015) add that it can be helpful to **identify potentially beneficial vs. potentially problematic interdependencies**.

Practical experiences

This chapter is based on practical experiences of Eurac Research and the University of Salzburg/Z_GIS in applying the *impact chain* concept based on the *Vulnerability Sourcebook* (Fritzsche et al., 2014) in various cooperation projects at national and sub-national scale. Furthermore, we integrated systematic feedback on applications of the *Vulnerability Sourcebook* and the *impact chain* approach, which was collected by Eurac Research as part of a GIZ project. Below we summarize some key factors contributing to a good application of the IC approach and discuss potential limitations and improvements. The assessed practical experiences can be grouped broadly into three categories:

- Understanding the context and the objective of an IC-based risk assessment and involving the right stakeholders in a participatory manner
- Methodological learning in applying the IC method
- Normalisation of indicators and aggregating indicators to a composite risk-indicator

The established categories are discussed in more detail below.

Understanding the context and the objective of an IC-based risk assessment and involving the right stakeholders in a participatory manner

A key factor in a successful application of the *impact chain* approach is a **good understanding and negotiation with the user on the objectives and the context of the climate risk assessment** and a **deep integration of users and stakeholder** in a participatory manner.

The most positively reported aspect involves a mixture of a strong participatory approach in preparing and scoping the assessment as well as in developing the *impact chains* with an indicator-based approach leading to a **tailor-suited semi-quantitative indicator-based assessment scheme for each specific case**. Due to their high participation, stakeholder mostly agree with the assessment results and feel committed to base an adaptation planning process on them. The systemic and graphic illustration of hazard, vulnerability and exposure factors through the *impact chains* allows users to better understand sensitivities, critical states and weak elements of the system/sector under assessment and helps to identify entry points for adaptation. Participatory processes are considered as an intermediate goal and valuable outcome per se and could be also understood as a capacity building activity for planning adaptation measures.

For a successful participatory process, it is important to **gather relevant regional/local expertise for the selected climate risks and sectors** (examples of such are agriculture, water management and tourism). On the national scale, this could include experts from national environmental ministries and agencies, line ministries and agencies, national statistical offices, national meteorological services, national universities as well as stakeholders from the private sector. All of them might also be data providers and, since data availability is often a bottleneck for the definition and population of indicators. Data availability should be discussed with them early in the process.

From previous experiences, we also learned that a deep and participatory risk assessment is a process which **needs time**. From a minimum of eight months for a very focused study (e.g. sub-national level, small number of spatial units, only one to two sectors) to at least one year for a national scale assessment. **The two major bottlenecks are stakeholder integration, which is a time-consuming process, and difficulties on data access and collection.**

Methodological learning in applying the IC method

In general, the IC-method was perceived as well described in the *Vulnerability Sourcebook* and the *Risk Supplement.* However, there are some **common misunderstandings and difficulties** in building the *impact chains* and defining the factors, which should be considered for future applications.

The first, and most important aspect is to set up the *impact chains* and the whole climate risk assessment as an **assessment comparing the current situation (current risk) with potential future situations (future risks)**. Risks and all underlying factors should be formulated in a way, that they catch the risk related to critical climate hazards **at a given time** (e.g. heavy rain, heatwaves and droughts) but **not** foremost on climate change (e.g. not rising temperatures). Only in this way, current climate related risks can be assessed and compared with future risk. The risk to climate **change** is then a result of the **changing risks**. E.g. a drought risk might be “moderate” today for a specific region but might get “high” in 2050 under a specific climate scenario. Starting with the assessment of current climate risks facilitates the integration of stakeholder knowledge in the system, since the stakeholders have experience and, hopefully, data on current climate risks. After the *impact chains* have been set-up based on the understanding of current climate risks, other factors should be evaluated considering **potential future climate situations that cannot be delineated from the current situation** (e.g. rising sea level).

Another key factor is the question on how **data-driven** the assessment can be. While data on climate hazard (e.g. drought) and exposure (e.g. population density) is often available for the current situation, data on vulnerability factors is often missing (e.g. absence or presence of water management plans). In this case, it must be evaluated if it is possible to conduct a survey on such factors or if an expert based assessment might be appropriate.

The description of future situations is characterized by critical aspects related to future vulnerabilities assumptions. While data for future climate is widely available, **projections on future socio-economic development** (e.g. population growth and land-use changes) is **hardly existing on sub-national levels and/or with appropriate certainty**. However, vulnerability might be as dynamic as climate and can highly contribute to climate risks. For instance, a further accumulation of assets and values in floodplains might increase the risk related to flood damages as much or even more than an increase in floods.

<u>Normalisation of indicators and aggregating indicators to a composite risk-indicator</u>

While the *impact chains* and the selection of indicators are an approach which worked very well in all practical applications and supported successfully adaptation planning, we perceived some **challenges in using the *impact chains* to conduct an assessment with aggregated composite indicators**.

Normalized composite indicators make sense if a risk assessment is used to c**ompare units through space and time**, e.g. districts within a country. In such cases, the core concept is to **normalize indicators into a unit-less scheme** (e.g. from 0-1) and aggregate them into **composite indicators**. In a first step, indicators are aggregated to the three risk components (hazards, vulnerability, exposure) and in a second step to a specific climate risk. The way indicators are normalized already represents a challenge. **We strongly recommend for every single indicator to use a value-based normalization, where "1" represents a critical value while "0" represents an uncritical value.** For this type of normalization, **critical thresholds** must be **defined**, ideally together with the stakeholders. However, there is **often no agreement or no expertise to define such thresholds**. As a **work-around**, often a simple **min-max normalization** is applied, which does not really allow comparability between factors.

Often the aggregation follows the **simplest approach of a weighted mean**. However, this approach is already challenging if stakeholders must agree on single weights. In the *Risk Supplement* (GIZ, 2017) we have proposed more **sophisticated aggregation methods** such as risk matrices, which prevent the problems of simple aggregation methods introducing a compensation of critical values by uncritical values. From our previous experiences the whole concept of **using composite indicators must be critically reviewed from case to case**. Only in the case of **comparative** studies having **high number** of spatial units (e.g. more than ten), such a composite indicator approach is required and makes sense. In case of a risk assessment having **few** cases, a more **qualitative** findings aggregation through integration of an indicator-based assessment with narratives might be much more target oriented and helpful to support adaptation planning.

Conclusion

The results of this literature review and the following course of UNCHAIN are supposed to improve the existing **impact chain** approach. Results from UNCHAIN can contribute to further improve the existing IC approach. Key elements are:

- a better integration of quantitative, semi-quantitative, qualitative and narrative approaches
- to consider and compensate the potential bias of the participatory elements within the assessment
- to include future vulnerability conditions based on socio-economic scenarios to better depict future critical conditions
- to address uncertainties and confidence levels for each step in the assessment
- to integrate knowledge from other approaches already existing in literature on the normalization and aggregation phases and the definition of critical thresholds

Particularly for more in-depth and scientific assessments it would be very interesting to forward the IC approach from a **'linear'** representation of risk components towards more **system dynamics-oriented models**.

After considering the results from the systematic literature review and the experiences made in the field, it becomes evident that the refinement of the approach should take place from **two** sides. **One** is the **design of participatory workshops** to be as fruitful as possible, and the **other** is the **improvement of data analysis**, i.e. methods and models. **Superordinate** to these two points, one should always consider **how best to communicate concepts, objectives, possibilities, limitations and results to stakeholders and end users**. The clearer these points are communicated, the more likely it is that the results of a risk assessment will be regarded as legitimate by decision makers and implemented in the form of adaptation measures or adjusted management practices.

When considering modelling **future risk** in general, the well know problems of **deep uncertainty** about future climatic and socio-economic conditions, as well as the lack of data – even of present conditions – were identified as the **major bottlenecks** of recent risk assessments. When looking at the development of *impact chains*, the difficulty of **identifying all relevant system elements** and their **interrelations** plays a central critical role. Even though **stakeholder involvement** is immeasurable, it is intrinsic to human nature, that they will bring in **selective perspectives**, may **lack better knowledge** and experience, and/or are **biased** in some way. This should be considered in the subsequent analysis. Furthermore, **methodical steps related to the data analysis** need to be **redesigned**, e.g. aggregation.

When we defined the search terms for this review, the idea was to keep them relatively open in order to include risk assessments from different domains. The idea was to, ideally, stumble upon approaches that are still relatively unknown in the community but might offer potential. This approach could be taken even further in the future, by looking into procedures carried out in completely other fields of science, like e.g. medicine.

References

Anandhi, A., Sharma, A., & Sylvester, S. (2018). Can meta-analysis be used as a decision-making tool for developing scenarios and causal chains in eco-hydrological systems? Case study in Florida. *Ecohydrology, 11*(7), e1997.

Apan, A., & McDougall, K. (2015). Vulnerability assessment and interdependency analysis of critical infrastructures for climate adaptation and flood mitigation. *International Journal of Disaster Resilience in the Built Environment*.

Bachner, G., Bednar-Friedl, B., Nabernegg, S., & Steininger, K. W. (2015). Economic evaluation framework and macroeconomic modelling. In *Economic Evaluation of Climate Change Impacts* (pp. 101-120): Springer.

Becker, D., Renner, K., & Schneiderbauer, S. (2014). Assessing and Mapping Climate Change Vulnerability with the Help of GIS: Example of Burundi. *GI_Forum*, 101-104.

Buth, M., Kahlenborn, W., Greiving, S., Fleischhauer, M., Zebisch, M., Schneiderbauer, S., & Schauser, I. (2017). Leitfaden für Klimawirkungs-und Vulnerabilitätsanalysen. *Dessau-Roßlau, Umweltbundesamt*.

Dawkins, E., André, K., Axelsson, K., Benoist, L., Swartling, Å. G., & Persson, Å. (2019). Advancing sustainable consumption at the local government level: A literature review. *Journal of cleaner production*.

Dawson, R. J. (2015). Handling interdependencies in climate change risk assessment. *Climate, 3*(4), 1079-1096.

Debortoli, N. S., Sayles, J. S., Clark, D. G., & Ford, J. D. (2018). A systems network approach for climate change vulnerability assessment. *Environmental Research Letters, 13*(10), 104019.

Dikanski, H., Hagen-Zanker, A., Imam, B., & Avery, K. (2016). *Climate change impacts on railway structures: bridge scour.* Paper presented at the Proceedings of the Institution of Civil Engineers-Engineering Sustainability.

Distefano, T., Riccaboni, M., & Marin, G. (2018). Systemic risk in the global water input-output network. *Water resources and economics, 23*, 28-52.

Dottori, F., Szewczyk, W., Ciscar, J.-C., Zhao, F., Alfieri, L., Hirabayashi, Y., . . . Betts, R. A. (2018). Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change, 8*(9), 781-786.

Field, C. B. (2014). *Climate change 2014–Impacts, adaptation and vulnerability: Regional aspects*: Cambridge University Press.

Fluixá-Sanmartín, J., Morales-Torres, A., Escuder-Bueno, I., & Paredes-Arquiola, J. (2019). Quantification of climate change impact on dam failure risk under hydrological scenarios: a case study from a Spanish dam. *Natural Hazards and Earth System Sciences, 19*(10), 2117-2139.

Fritzsche, K., Schneiderbauer, S., Bubeck, P., Kienberger, S., Buth, M., Zebisch, M., & Kahlenborn, W. (2014). The Vulnerability Sourcebook: Concept and guidelines for standardised vulnerability assessments.

Gies, L., Agusdinata, D. B., & Merwade, V. (2014). Drought adaptation policy development and assessment in East Africa using hydrologic and system dynamics modeling. *Natural hazards, 74*(2), 789-813.

GIZ, E. (2017). Risk Supplement to the Vulnerability Sourcebook. *Guidance on How to Apply the Vulnerability Sourcebook's Approach with the New IPCC AR5 Concept of Climate Risk*.

Greiving, S., Zebisch, M., Schneiderbauer, S., Fleischhauer, M., Lindner, C., Lückenkötter, J., . . . Schauser, I. (2015). A consensus based vulnerability assessment to climate change in Germany. *International Journal of Climate Change Strategies and Management*.

Haddaway, N. R., Macura, B., Whaley, P. and Pullin, A. S. (2017). ROSES flow diagram for systematic reviews. Version 1.0. , 2017. DOI: 10.6084/m9.figshare.5897389.v3

Haddaway, N., Woodcock, P., Macura, B., & Collins, A. (2015). Making literature reviews more reliable through application of lessons from systematic reviews. *Conservation Biology, 29*(6), 1596-1605.

Hagenlocher, M., Schneiderbauer, S., Sebesvari, Z., Bertram, M., Renner, K., Renaud, F. G., . . . Zebisch, M. (2018). Climate Risk Assesment for Ecosystem-based Adaptation: A guidebook for planners and practitioners.

Hedlund, J., Fick, S., Carlsen, H., & Benzie, M. (2018). Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk. *Global environmental change, 52*, 75-85.

Hussain, S. S. (2014). Adapting to climate change: a new tool for communities. *Appropriate Technology, 41*(3), 36.

Kabisch, S., Chakrabarti, R., Wolf, T., Kiewitt, W., Gorman, T., Chaturvedi, A., & Arora, R. (2014). Climate change impact chains in the water sector: observations from projects on the East India coast. *Journal of water and climate change, 5*(2), 216-232.

Kang, Y., & Park, C.-S. (2018). A Multi-Risk Approach to Climate Change Adaptation, Based on an Analysis of South Korean Newspaper Articles. *Sustainability, 10*(5), 1596.

Kienberger, S., Borderon, M., Bollin, C., & Jell, B. (2016). Climate change vulnerability assessment in Mauritania: reflections on data quality, spatial scales, aggregation and visualizations.

Koks, E., Thissen, M., Alfieri, L., De Moel, H., Feyen, L., Jongman, B., & Aerts, J. (2019). The macroeconomic impacts of future river flooding in Europe. *Environmental Research Letters, 14*(8), 084042.

Lapola, D. M., Pinho, P., Quesada, C. A., Strassburg, B. B., Rammig, A., Kruijt, B., . . . Marengo, J. A. (2018). Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. *Proceedings of the National Academy of Sciences, 115*(46), 11671-11679.

Lissner, T. K., Holsten, A., Walther, C., & Kropp, J. P. (2012). Towards sectoral and standardised vulnerability assessments: the example of heatwave impacts on human health. *Climatic change, 112*(3-4), 687-708.

Lozoya, J., Conde, D., Asmus, M., Polette, M., Píriz, C., Martins, F., . . . Anello, L. (2015). Linking social perception and risk analysis to assess vulnerability of coastal socio-ecological systems to climate change in Atlantic South America. *Handbook of Climate Change Adaptation. Berlin, Germany: Springer*, 373-399.

Lückerath, D., Bogen, M., Rome, E., Sojeva, B., Ullrich, O., Worst, R., & Xie, J. (2018). *The RESIN climate change adaptation project and its simple modeling approach for risk-oriented vulnerability assessment.* Paper presented at the Workshop.

Moglia, M., Nguyen, M., Neumann, L., Cook, S., & Nguyen, T. (2013). *Integrated assessment of water management strategies: framework and case study.* Paper presented at the 20TH INTERNATIONAL CONGRESS ON MODELLING AND SIMULATION (MODSIM2013).

Olabisi, L. S., Liverpool-Tasie, S., Rivers, L., Ligmann-Zielinska, A., Du, J., Denny, R., . . . Sidibé, A. (2018). Using participatory modeling processes to identify sources of climate risk in West Africa. *Environment Systems and Decisions, 38*(1), 23-32.

Pant, R., Hall, J. W., & Blainey, S. P. (2016). Vulnerability assessment framework for interdependent critical infrastructures: case-study for Great Britain's rail network. *European Journal of Transport and Infrastructure Research, 16*(1).

Parry, M., Parry, M. L., Canziani, O., Palutikof, J., Van der Linden, P., & Hanson, C. (2007). *Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC* (Vol. 4): Cambridge University Press.

Rome, E., Bogen, M., Lückerath, D., Ullrich, O., Worst, R., Streberová, E., . . . Carter, J. (2019). Risk-based analysis of the vulnerability of urban infrastructure to the consequences of climate change. In D. Gritzalis, M. Theocharidou, & g. Stergiopoulos (Eds.), *Advanced Sciences and Technologies for Security Applications. Critical Infrastructure Security and Resilience: Theories, Methods, Tools and Technologies* (pp. 55-75). Retrieved from https://www.springer.com/us/book/9783030000233

Rome, E., Ullrich, O., Lückerath, D., Worst, R., Xie, J., & Bogen, M. (2018). *IVAVIA: impact and vulnerability analysis of vital infrastructures and built-up areas.* Paper presented at the International Conference on Critical Information Infrastructures Security.

Romero-Lankao, P., & Norton, R. (2018). Interdependencies and risk to people and critical food, energy, and water systems: 2013 flood, Boulder, Colorado, USA. *Earth's Future, 6*(11), 1616-1629.

Schneiderbauer, S., Pedoth, L., Zhang, D., & Zebisch, M. (2013). Assessing adaptive capacity within regional climate change vulnerability studies—an Alpine example. *Natural hazards, 67*(3), 1059-1073.

Schwarze, R. (2015). On the State of Assessing the Risks and Opportunities of Climate Change in Europe and the Added Value of COIN. In *Economic Evaluation of Climate Change Impacts* (pp. 29-42): Springer.

Steininger, K. W., Bednar-Friedl, B., Formayer, H., & König, M. (2016). Consistent economic cross-sectoral climate change impact scenario analysis: Method and application to Austria. *Climate Services, 1*, 39-52.

Tapia, C., Abajo, B., Feliu, E., Mendizabal, M., Martinez, J. A., Fernández, J. G., . . . Lejarazu, A. (2017). Profiling urban vulnerabilities to climate change: An indicator-based vulnerability assessment for European cities. *Ecological indicators, 78*, 142-155.

Thacker, S., Kelly, S., Pant, R., & Hall, J. W. (2018). Evaluating the benefits of adaptation of critical infrastructures to hydrometeorological risks. *Risk Analysis, 38*(1), 134-150.

Tonmoy, F., & El-Zein, A. (2013). *Vulnerability of infrastructure to sea level rise: a combined outranking and system-dynamics approach.* Paper presented at the Proceedings of the 22nd Conference on European Safety and Reliability (ESREL-2013), Amsterdam, The Netherlands.

Tsavdaroglou, M., Al-Jibouri, S. H., Bles, T., & Halman, J. I. (2018). Proposed methodology for risk analysis of interdependent critical infrastructures to extreme weather events. *International journal of critical infrastructure protection, 21*, 57-71.

Wahab, A., & Ludin, A. M. (2018). *Flood vulnerability assessment using artificial neural networks in Muar Region, Johor Malaysia.* Paper presented at the IOP Conference Series: Earth and Environmental Science.

Yokohata, T., Tanaka, K., Nishina, K., Takahashi, K., Emori, S., Kiguchi, M., . . . Masaki, Y. (2019). Visualizing the interconnections among climate risks. *Earth's Future, 7*(2), 85-100.

User interface and stakeholder involvement

Introduction

In this chapter we will identify challenges and knowledge gaps related to **user interface and stakeholder involvement**, contributing primarily to a **refined** and a **structured method of knowledge co-production to be integrated into impact modelling**.

Despite more sophisticated climate projections and a wealth of climate change adaptation (hereafter adaptation) research developed since the beginning of the 21th century, **further efforts are required to bridge the gap between research and action** (Klein and Juhola 2014; Palutikof et al. 2019; Runhaar et al. 2018). To come to terms with the lack of **actionable knowledge** (Ernst et al. 2019) there is a pressing need for **tailored climate information and services** that can guide and inform adaptation planning processes (Mastrandrea et al. 2010). However, further research is needed to understand **how intended users of climate information can be meaningfully involved throughout the stages of research** and by tailoring the information to relevant institutional and decision contexts (Hewitt et al. 2017; Palutikof et al. 2019).

At the same time, there is a great demand for and interest in **bottom-up approaches** and **knowledge co-production** in relation to a number of complex sustainability and environmental issues (Bremer and Meisch 2017; Lang et al. 2012; Norström et al. 2020; Rodela and Gerger Swartling 2019), and more specifically climate change adaptation research (Bremer and Meisch 2017). In the literature several **benefits** are associated with the application of **participatory research approaches**. As summarized by Cvitanovic et al (2019), these include: making science more accessible to decision-makers; increasing the perceived saliency, credibility and legitimacy of research outcomes; facilitating inclusion of multiple knowledge systems; and fostering learning.

Yet, an **inconsistent** terminology, and a **lack of reflection** and **clarity** on how the concept of co-production is interpreted and applied **complicates** learning from and improving practice (Norström et al. 2020). As a first step, there is a need for **increased reflexivity** and **transparency** among scholars adopting co-production approaches about how and when its used (Bremer and Meisch 2017). Moreover, as discussed by Lang et al (2012), even though lessons learned can be transferred and often are valid in many circumstances, **more knowledge is needed on what works in different contexts**: “In fact, mutual learning among the different researchers needs to be established and learning processes beyond the boundaries of individual projects must take place” (Lang et al. 2012, p.40).

Consequently, by reviewing international research including academic and grey literature we **explore the role of knowledge co-production in climate change risk assessments to better inform decision-making and adaptation action**. Through the review we will address the following **research questions**:

- What is the evidence of the role of knowledge co-production in climate change risk assessment to inform adaptation decision-making and action? Are there any evidence/knowledge gaps?
- What challenges and opportunities to knowledge co-production in these assessments can be identified (to better inform adaptation decision-making and action)?

With starting point in the IPCC 5th Assessment Report (IPCC 2014), we refer to climate change risk assessment in a broad sense where risks are a “result from the interaction of vulnerability, exposure, and hazard" (Field et al. 2014, p.1048). Thus, when we refer to climate change risk assessment this could be any form of qualitative or quantitative assessment that aims to estimate, identify or appraise climate change risks, impacts, vulnerabilities or adaptation. Moreover, it encompasses studies developed to generate better understanding and awareness of climate risks in specific sectors or regions, and studies that focus on appraisal of adaptation options, including but not limited to studies on climate services.

With its rich history spanning decades of research and practice across multiple disciplines, **co-production** is an inevitable and **ubiquitous feature of modern societies** (Miller and Wyborn 2018). Indeed, when reviewing scientific as well as grey literature (e.g. technical reports, strategy documents, planning documents and guidebooks on adaptation), co-production is a **well-established method** for inclusion of practitioners (EEA 2013; Kingston and Cavan 2011; Prutsch et al. 2014; Taylor et al. 2017). This is an expression of an increased interest in different forms of integrative approaches to knowledge production during the last decades (Bremer and Meisch 2017; Lang et al. 2012; Norström et al. 2020) not least in research pertaining to climate change adaptation (Bremer and Meisch 2017). This can be seen as part of a broader shift of the **role of science** in society (Jasanoff 2004) with larger emphasis on societal relevance and applicability, thus science has become accountable to society in much broader ways than previously (Barry et al. 2008; Mobjörk 2010; Nowotny et al. 2003; Wiek et al. 2014). As put forward by McNie (2007) there is a call for "a new social contract for science /…/ our awareness of the complexity and interconnectedness of environmental problems is prompting calls for more integrated science policy that includes a broader range of stakeholders." (McNie 2007, p.31). Still, the applicability of the principles of co-production in adaptation action faces a number of obstacles, not least what can be called the **inclusion/ exclusion problem**: Who (and based on what knowledge) gets to include – or exclude – specific concerns, risks, issues and foci; and how does non-academic knowledge weigh when facing the methodological stringency of scientifically produced knowledge?

Being described as a "multifaceted phenomenon" (Bremer and Meisch 2017, p.12) there is generally a lack of coherence across academic disciplines as regards to how knowledge co-production (and related concepts such as Mode 2 research (Gibbons et al. 1994; Nowotny et al. 2001) or post-normal science (Funtowicz and Ravetz, 1993)) is defined and put into practice (Bremer and Meisch 2017; Norström et al. 2020). However, according to Vincent et al (2018 p. 52) knowledge co-production processes may encompass the following six characteristics:

- A means of addressing complex problems
- A means of producing knowledge
- A means of producing knowledge and governance systems
- A means of recognising different knowledges Involves collaboration among various actors
- Is contingent upon trusted relationships
- Is a social learning process

A seventh characteristics could be added, namely the process through which particular knowledge(s) are included or excluded which should, to ensure that co-production principles are followed, go beyond the stringent definitions of salient knowledge from scientific methodology.

One recent definition of knowledge co-production is proposed by Norström et al (2020, p.2) as being an "Iterative and collaborative processes involving diverse types of expertise, knowledge and actors to produce context-specific knowledge and pathways towards a sustainable future.” Similarly, Lang et al. (2012, p.27) suggest that “transdisciplinary research needs to comply with the following requirements: (a) focusing on societally relevant problems; (b) enabling mutual learning processes among researchers from different disciplines (from within academia and from other research institutions), as well as actors from outside academia; and (c) aiming at creating knowledge that is solution-oriented, socially robust (see, e.g., Gibbons 1999), and transferable to both the scientific and societal practice.” Thus, when we refer to knowledge co-production processes, this include **transdisciplinary** and **participatory** research approaches that **transcend the divide between academia and society** by involving **multiple knowledge perspectives** in the research (c.f. Hegger et al. 2012; Norström et al. 2020; Wiek et al. 2014).

Bremer and Meisch (2017) investigated how knowledge co-production is used in climate change research starting from and adding further nuance to the two broad areas of so called **‘descriptive’** and **‘normative’** approaches (see also Wiek et al. 2014). The former can be described as an area that “uses the co-production idiom for interpreting the shifting relationships between science, society, and nature—including around climate change—rather than intervening to actively change these relationships” (Bremer and Meisch 2017, p.23). The latter, normative approach (that are in focus in this review) can be seen as having a **problem solving** focus (Mobjörk 2009) or research design focus (Wiek et al. 2014) with the aim to ”elaborate guidelines (in the most general sense) of how different actors should define and co-produce relevant knowledge” (Bremer and Meisch 2017, p.23).

Bremer and Meisch (2017) found that **adaptation research** is commonly related to the **normative** approach even though few studies explicitly states or elaborate upon these matters. However, considering the complexity and ambiguity of how the concept of co-production is applied, they also identify **eight** distinct yet partly overlapping lenses (or perspectives) that underpin climate change research. The **dominating** lens in adaptation research is ‘the **iterative interactive** lens’ that can generally be seen as driven by the demand to **bridge the gap between science and action**, increasing the usability of the research. This is followed by ‘the **institutional** lens’ that looks into aspects of governance and building adaptive capacity and ‘the **extended science** lens’ that emphasize the need for integrating multiple knowledge perspective. In addition, the authors identify three additional lenses: ‘s**ocial learning**’, **‘empowerment’** and ‘**public service**’. It is common though that elements from several lenses are identified in the same study.

Moreover, the authors conclude that, depending on which perspective that is in focus, the criteria for evaluating the success of the process differs. The iterative interaction lens should be “assessed relative to the usability of climate information products in a decision-making context” and the extended science lens should be ”… measured against the social robustness, accountability, and legitimacy of scientific knowledge in the face of uncertainty.” (Bremer and Meisch 2017, pp.8–9).

This review offers a **complementary** review to that of Bremer and Meisch (2017) by focusing specifically on **empirical studies related to knowledge co-production and climate change risk assessment** (that is, studies under the **normative** divide). As such, this is a review of **how adaptation strategies are implemented and the way operationalization of methodological and theoretical stances is carried out in practice**, hence the inclusion of selected grey literature contributions on the matter.

Method

The part of this review that included **peer-reviewed** contributions was conducted by adopting a 'systematic review approach' building on principles from systematic review and mapping methods (Haddaway et al., 2015). For further details about the steps included in the approach see chapter 2 (adapted list from Dawkins et al, 2019 in chapter 2.2).

Firstly, a review protocol was developed specifying the aim and research questions to be addressed by the review. We also identified key concepts for the search as well as selection criteria. The protocol was shared and discussed by the SEI research team and Unchain partners: Western Norway Research Institute (WNRI), University of Salzburg (PLUS) and Nordland Research Institute (NRI). Two **main concepts** were determined for the search: 1) **knowledge co-production** and 2) **risk assessment**. To create a search string of these concepts a list of possible synonyms were identified (see Appendix, table A-1). This was based on the authors' previous experience, by checking different terms used in a selection of articles and through a survey distributed to Unchain case study coordinators.

Secondly, the search string was tested in the search platform of Web of Science (WoS) Core Collection and Scopus abstract and citation database. Before the final search string was established and applied it was refined by excluding for example the synonym "collaborate"which reduced the number of documents retrieved from more than 50 000, to fewer than 10 000.

The search string applied was:

> (("Knowledge co$produc*" OR "Co$produc* of knowledge" OR "Joint* knowledge produc*" OR "Science$policy interface" OR "Participat* action research" OR "Stakeholder engage*" OR "Stakeholder integrat*" OR "Stakeholder participat*" OR "Science$stakeholder process*" OR "Stakeholder interact*" OR "Science$practice interact*" OR "Transdisciplin*" OR "User interface" OR "Co$design" OR "Co$creat*" OR "Co$explorat*" OR "Science$practice interface" OR "Participat* approach*") AND (("Assess*" OR "apprais*") AND ("risk*" OR "vulnerabl *" OR "impact*" OR "multi$sector assess*" OR "multi$risk" OR "adapt*" OR "hazard*" OR "resilience")))

The search yielded 7063 documents in Scopus and 2320 documents in WoS. The documents were all uploaded to EPPI-Reviewer 4 (a software for systematic reviews) and a total of 1893 duplicates were removed. The search was limited to the following basic conditions: (1) the search period was set to 2014-2019, reflecting the launch of the latest IPCC Report in 2014, (2) the language had to be in English, and (3) geographical location was set to countries within the OECD. Hence, all studies that did not fulfil these criteria were excluded in the screening phase.

Thirdly, to select articles for full text analysis all remaining 7012 documents were screened on title and abstract. This was done by one of the researchers in dialogue with the research team. The eligible criteria presented was applied (in addition to the basic conditions as specified above): actors, intervention, subject and setting (Table 3). The first criterion - '**actors'** - meant that for inclusion of the article, any type of stakeholders with an active participating role in the study should be considered. Conceptual studies or studies on stakeholders were hence excluded. The second criterion was the type of 'intervention' considered by the studies which referred to any interventions linked to climate change (e.g. assessments of climate change risks, impacts or vulnerability, adaptation appraisal etc.). Studies that did not concern climate change were excluded. The third criterion specified the 'study subject'. Since Unchain case studies are cross-sectoral and covers different types of climate risks at different governmental levels we chose not to specify any exclusion criterion. The fourth and final criterion referred to 'setting' and as already mentioned meant that only studies conducted in any of 39 OECD countries was included. In total 89 documents were included after the initial screening of title and abstract.

Table 3 *Criteria applied for title and abstract screening*

Parameters	Inclusion criteria
Actors	Stakeholders (or equivalent) must be included as an actor in the study Stakeholders must have an active role, participating, rather than a passive or solely observational role
Intervention	Any interventions linked to climate change risk assessment (or equivalent)
Study subject	This study subject can be a sector, region, groups of people etc. at local to international levels The study can be for any climate change related risks or impacts
Setting	Studies must be from one of the OECD countries Studies must be in English

Ideally, the screening is made by several researchers to allow for cross-checking of the inclusion criteria. However, in this case the screening was conducted by only one reviewer, yet several meetings were held during the process with a second reviewer to check for consistency. In addition, all 89 documents were screened a second time by two of the reviewers excluding additional 20 document. For a schematic picture of the document selection process see figure 8.

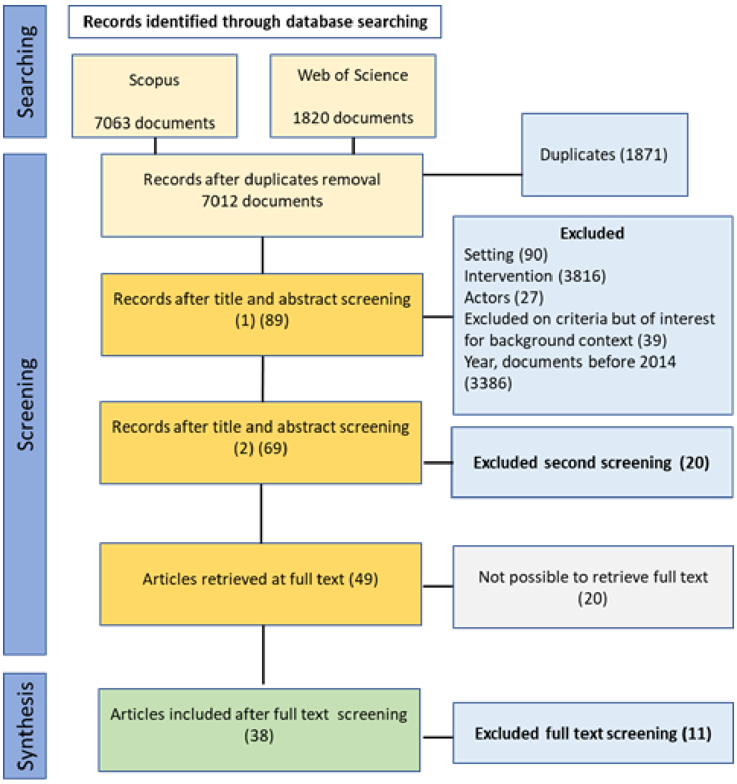


***Figure 8** Results of the document selection process adapted from Haddaway et al (2017)*[1]

In the next step all documents were coded by the research team (in total five researchers) based on a predefined coding form (see Appendix, table A-2), and then synthesized in the light of the research questions as specified above. First, basic citation information and content were registered. Secondly, we collected descriptive data of the studies including countries, governance levels, sectors, and climate risks in focus. We also identified types of stakeholders involved, methods used for their involvement and, if stated, their role in the assessments. Attention was paid to whether and how the knowledge co-production process, or its outcomes (see e.g. Hegger et al. 2012) was evaluated and if so, what the results of these evaluations were. Even though outcomes may be difficult to capture, we looked at both direct outputs of the co-production process for example in the form of products but also other types of outcomes such as capacity building (Wiek et al. 2014). Finally, we coded challenges and opportunities or enabling factors to knowledge co-production as identified in the studies. The analysis of the full texts was made through an inductive approach where emerging themes was identified and clustered for presentation in the results section.

As for the selection of **grey** literature for the review, a combination of boolean searches based on the keywords described above, in-text snowballing (Blaikie, N. 2010; Easterby-Smith, M., Thorpe, R., & Jackson, P. R. 2008) and referencing was used to come up with a relevant and adequate number of contributions assessed to be indicative of how co-production (or similar and comparable) methodology. The criteria applied for title and abstract screening adhered to the ones used for the peer reviewed literature, with the obvious adjustment that not all grey literature will qualify as a study with the same degree of methodological and analytical rigor. Still, important inclusion/ exclusion parameters are comparable, noticeably the assessment of (degree of) stakeholder participation (i.e. adhering to the specification noted above, that it should be a work with, not on, stakeholders and actors), the extent to which specific interventions with regards to climate change risk assessment has been implemented/ suggested, and that it has been possible to identify sectors and regions relevant to (or comparable to) the Unchain field site portfolio. A limiting factor that we assess to have had a stronger exclusion consequence for grey literature than for peer reviewed work has been the requirement that the work should be available in English, as much strategic, management and assessment reporting of implementation of risk aversion measures is produced in native languages.

In addition to assessing peer reviewed literature, a sample of regional grey literature concerning development trends and challenges – including climate change adaptation – in the **Arctic** suggests that the **multiple concerns** and **challenges** facing regions are met to a **varying degree** with **co-production** and **inclusive** methods, both with regard to the identification of relevant threats and potential solutions. Thus, a selected number of reports on Arctic development has been included here, meant to exemplify. It is also interesting to find that **most** of the grey literature found in searches focuses on **non-European**, even **non-OECD** countries. Indeed, **many** reports focuses on how to **implement co-production practices** in the **global south**, that is, as part of an effort to build local, regional or even national resilience and adaptation capacity (see McClure, A. 2018; Nakashima et al.

[1] Note that one study was included at a later stage in the process through an additional cross-checking of the excluded documents. Therefore, the total number of articles included after full text screening should be 39.

2012; Carter et al. 2018; Provia 2013). But also here, the extent to which **co-production measures** are implemented are **limited**, as the main focus seems to be on **participatory stakeholder arrangements** where practitioners are actively engaged ‘in both ends’ of the process, that is, as providers of data initially, and as receivers of tools, solutions, ‘best practices’ and – where available – supporting infrastructure and/ or financial aid (ibid).

Scientific discourse

<u>Countries and governance levels represented</u>

In reviewing the basic description of all 39 research documents included for full text screening (see Appendix for full reference of all articles that were included), we find that 19 out of 36 OECD countries were represented. Most case studies are conducted in **UK** and **Australia**, following, **USA** and **Netherlands**. Some articles included case studies in several countries - see figure below.

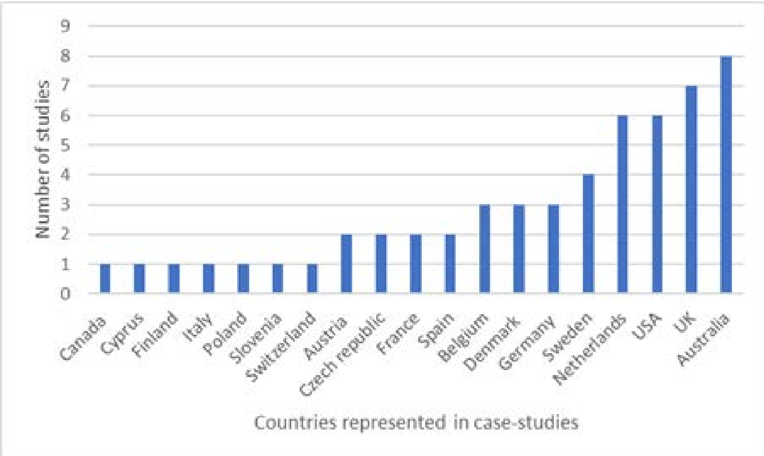


Figure 9 *Countries within the OECD represented in studies included in the review*

Most of the studies focused their attention and intervention on a **local** governance level, i.e. local community’s flood risk assessment (see figure below). This is an expected result considering the context-based and local character of knowledge (Potts 2001) as well as adaptation processes, especially from the perspective of knowledge co-production (c.f. Bremer and Meisch 2017). In the grey literature included, most are focused on the development in specific regions or industries, combined with national/ EU-level strategies and priorities. Several of the documents reviewed are sub-reports or documentation of results, including the development of toolkits and/ or strategies (see section on policy below).

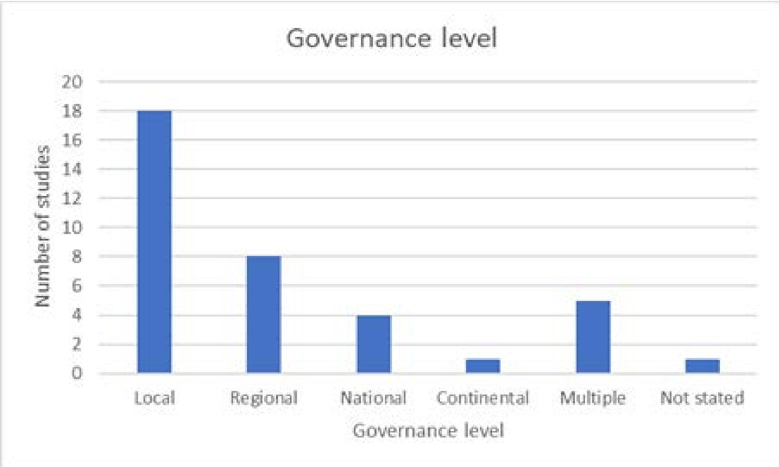


***Figure 10** Governance level represented in case studies*

Rationale or motivation to stakeholder engagement in the assessment

All studies included involves **stakeholders** to some extent - yet the composition of them is diverse. Generally, stakeholder groups represented are somehow potentially **impacted** by climate change risk on a local level, such as lay people or authorities from local communities i.e. community leaders (Brown et al. 2016). Other representatives are **experts** from key sectors, for example flood risks- or coastal managers, emergency sector or water experts. This latter point is relevant also for the grey literature descriptions where practitioners often means key sector specialists, especially when projects have aimed for increased resilience and adaptational capacities for industries and/ or specific community services.

The **role** of stakeholders in the assessments is not always explicitly mentioned, however it **spans** from participation in the **problem definition** (for example widening the scope of the problem) to **appraisal and prioritizing of adaptation planning** (e.g. Barquet et al. 2018; Boezeman et al. 2014). Main rationales for involving stakeholders are to bring together different interests and concerns; learn from each other's different perspectives; and build trust to foster understanding of the adaptation planning or risk. Other common motivations mentioned are to better understand stakeholders' perceptions of risks and impacts and to better understand barriers of adaptation actions.

Another aspect that we investigated was which t**ype of intervention** that was undertaken in the studies, which referred to any assessments (or similar) of climate change risks, impacts or vulnerability or appraisal of adaptation options. The result shows that interventions included primarily: i) **risk** or **vulnerability assessment** models, frameworks or tools, or ii) **participatory** frameworks or methods i.e. scenario building. Aiming at: addressing knowledge gaps, increase and support capacity building, mapping risks and vulnerabilities, support adaptation planning and decision-making, address risk management and understanding stakeholders' perception of adaptation measures.

Evaluation of the co-production process and outcomes

Less than half of the reviewed studies have **evaluated the participatory process itself**, and even **fewer** have evaluated the **outcome** of the process (see figure below). Also, in grey literature there is little mention of specific assessments of the participatory processes themselves; one notable exception being an EU-financed study of the resilience of historic (urban) areas in the EU (ARCH 2019). Here, specific principles for inclusion is embedded in the methodology itself, focusing on co-production qualities as valuable for the strengthening of resilience and adaptive capacity. Another highly relevant exception is the report from the RESIN project, which is a detailed account of precisely how a project design, framework and output changes when co-creation methodology is thoroughly implemented (RESIN 2018). While referring to the 'implementation' or 'useability' gap in climate change adaptation literature (p. 17), the project sets forth to enable the inclusion of co-creation approach with the aim on meeting the needs of both decision makers and practitioners. The **most common** approach in the scientific literature is a **retrospective** and **qualitative** evaluation such as interviews and post-workshops. Few studies have made an evaluation both pre and post in the participatory process, in order to identify changes in, e.g. knowledge or understanding, before and after the project (e.g. Fatorić and Seekamp 2019; Yusuf et al. 2018). This suggests that, in order to gain understanding of the potential effect, efforts are needed to embed both **pre**-and **post**-evaluation.

However, the research that evaluated the process and/or its outcomes point to **effects** on **raising awareness and understanding among the stakeholders**, as well as an **appraisal** of adaptation planning and identifying climate change induced risks (e.g. Barquet et al. 2018; Bitsura-Meszaros et al. 2019). An example of an outcome like raising awareness, or rather lack of, can be seen in a quote from Yusuf et al. (2018, p.118) "…at an aggregate, community-wide level, there was little impact on participants' perception of the community's willingness to act. This result highlights the importance of both social learning and building social capital". Hegger and Dieperink, (2014, p.12) conclude that "actually measuring knowledge production is challenging". They also highlight the importance of building networks: "Most successful projects managed to build a large network of actors, including actors from science and policy" and "that a range of resources should be employed to increase success" (2014, p.34).

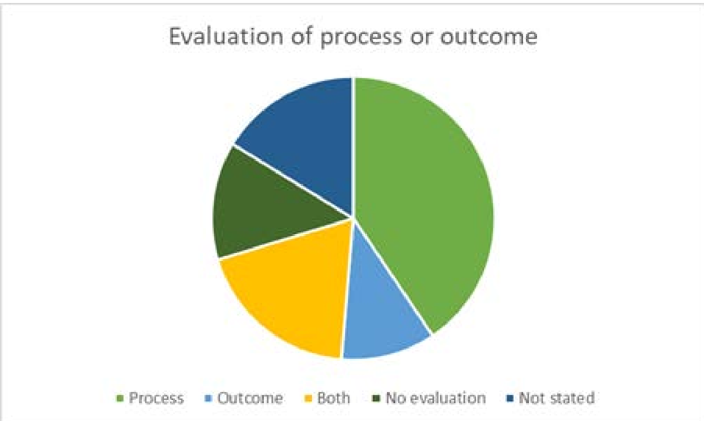


Figure 11 *Evaluation of process versus outcome of the participatory involvement*

<u>Challenges to knowledge co-production</u>

During the full text analysis, **five** overarching themes of **challenges** to knowledge co-production were identified, see table below. These represent a selection of the most common themes found in the included literature. A few of the studies have evaluated both the outcome and the process which give valuable additional insights. However, even studies that have not explicitly evaluated the process, contributes with interesting perspectives on challenges involved. Only one in five studies did not state any challenges at all, hence, most of the reviewed ones did.

It is evident that one **major concern** is the **extent** to which **stakeholders are represented** (cf. **challenge 1** in the table above).[2] In many cases it has been hard to gather a group of stakeholders that represents all the impacted groups and safeguard diversity and equal gender quota (e.g. Bitsura-Meszaros et al. 2019; Gruber et al. 2017; Riddell et al. 2019). Brink et al. (2018) identify that the challenge of enabling accurate representation of stakeholders can also include the economic prerequisite for stakeholders to be involved, furthermore, they might need the approval from their organizations. Power dynamics in a group can also be a barrier for success and the participatory process need to facilitate addressing the issue (Boezeman et al. 2014).

The **second** most common challenge identified is the **contrasting perception in scale and scope** of the project (cf. **challenge 2**). One example of this is the **time horizon** for production of scientific knowledge and results, compared to a decision-making context for a municipality (e.g. Barquet et al. 2018).

Table 4 *Most common themes of identified challenges for knowledge co-production*

Challenges ranked by how often they are referred to in the literature	Number of studies	References
1. Stakeholder representation and diversity, power dynamics in the group	15	Boezeman et al. (2014), Boeraeve et al. (2018), Brink et al. (2018) Bitsura-Meszaros et al. (2019), Barquet et al. (2018), Fatoric and Seekamp (2019), Gruber et al. (2017), Mitter et al. (2014), Pasquier et al. 2020, Penning-Rowsell et al. (2014), Prutsch et al. (2018), Ridell et al. (2019), Singh-Peterson et al. (2016), Verkerk et al. (2017), Yusuf et al. (2018)
2. Scale and scope of project in time and geographically site specific vs. too broad	14	Bracken et al. (2016), Brown et al. (2016), Boeraeve et al. (2018), Barquet et al. (2018), Galford et al. (2016), Hemmerling et al. (2019), Leitch et al. (2019), Pasquier et al. (2020), Penning-Rowsell et al. (2014), Robinson et al. (2016), Rodriguez et al. (2014), Van de Ven et al. (2016), Yusuf et al. (2018), Hegger and Dieperink et al. (2014)
3. Common understanding and problem definition	7	Bracken et al. (2016), Mitter et al. (2014), Penning-Rowsell et al. (2014), Prutsch et al. (2018), Sorensen et al. 2016, Gerger Swartling et al. (2019), Glaas and Jonsson (2014)
4. Communication, transdisciplinary project demands effort by the participants	7	Boeraeve et al. (2018), Barquet et al. (2018), Gerkensmeier and Ratter (2018a), Maskrey et al. 2016, Prutsch et al. (2018), Sorensen et al. (2016), Gerger Swartling et al. (2019)
5. Legitimacy, for example locally relevant and reliable data, models capture uncertainty	8	Becu et al. (2017), Barquet et al. (2018), Robinson et al. (2016), Rodriguez et al. (2014), Söderholm et al. (2018), Van de Ven et al. (2016), Verkerk et al. (2017), Hegger and Dieperink et al. (2014)

[2] It is interesting to note that this concern has not been raised in the grey literature reviewed, where focus has been on showing that representation has been secured rather than problematizing its representativity- One reason for this may be that for these presentations of projects/ strategies, the goal concerning representation is to show that they have practitioners and stakeholders involved, not adhering to principles more fundamental to academic discourse on the 'quality' of stakeholder representation as such.

6. No barriers specified	6	Carmichael et al. (2018), Gerkensmeier and Ratter (2018b), Jacobs et al. (2018), Lorencova et al. (2018), Muir et al. (2014), Ronco et al. (2015)

Another common challenge found in the literature is **lack of common understanding of the problem definition** (cf. **challenge 3**). For example, Glaas and Jonsson describe this as differences in expectations of the project goal: "this seems to have resulted from unspoken positions and expectations that were not thoroughly addressed in the initial and ongoing discussions of realistic and desired project aims and outcomes" (Glaas and Jonsson 2014, p.181). This challenge may also be manifested in a lack of understanding of stakeholder site-specific needs as opposed to large-scale generic flood prevention (Bracken et al. 2016). To overcome this challenge the authors call for '**sustained connections'** between **local communities and professionals**: "There is ample opportunity for professionals to make more and sustained connections with local communities" (Bracken et al. 2016, p.253).

Other challenges identified relate to variable knowledge and understanding in a diverse group of stakeholders which demands **extensive communication efforts** (cf. **challenge 4**) (e.g. Boeraeve et al. 2018; RESIN 2018). Similarly, Barquet et al. (2018, p.210) emphasise the challenge of finding a common vocabulary, "the term 'return period' is not intuitive and is often misleading to a non-expert audience. Stake-holders immediately assume that a 100-year return period meant that an event would not happen until the next century".

Another challenge raised in several studies is the lack of common understanding and poor communication generally in the process, leading to **doubts in the legitimacy** of for example model outputs (cf. **challenge 5**). If the information used as input data is hard to access and understand for stakeholders, the output and result can be considered as unreliable and not locally relevant (Robinson et al. 2016). Rodriguez et al (2014, p.58) give another example of the challenge of questioned legitimacy with farmers finding "long-term projections of limited relevance while under pressure to resolve more immediate day-to-day and season-to-season decisions".

Opportunities and enabling factors

Most of the studies have identified **opportunities** and **enabling** factors. Some common themes identified included: validation of model results, increased legitimacy and trust, use of knowledge brokers as a factor for success. These themes will be further discussed and explained in this section, see table below.

Table 5 *Most common themes of identified opportunities and enabling factors*

Opportunities and enabling factors ranked by how often they are referred to in the literature	Number of studies	References
1. Stakeholder group composition	17	Boezeman et al. (2014), Bracken et al. (2016), Brown et al. (2016), Boeraeve et al. (2018), Carmichael et al. (2018), Galford et al. (2016), Gerkensmeier and Ratter (2018b), Gruber et al. (2017), Hemmerling et al. (2019), Lorencova et al. (2018), Maskrey et al. (2016), Muir et al. (2014), Pasquier et al. (2020), Gerger Swartling et al. (2019), Glaas and Jonsson (2014), Hegger and Dieperink (2014), Yusuf et al. (2018)
2. Increased understanding of perspectives, building trust and increase legitimacy	15	Boezeman et al. (2014), Boeraeve et al. (2018), Brink et al. (2018), Carmichael et al. (2018), Fatoric and Seekamp (2019), Galford et al. (2016), Gerkensmeier and Ratter (2018a), Gerkensmeier and Ratter (2018b), Gerger Swartling et al. (2019),

		Gruber et al. (2017), Leitch et al. (2019), Lorencova et al. (2018), Maskrey et al. (2016), Muir et al. (2014), Yusuf et al. (2018)
3. Validation, appraisal	9	Boezeman et al. (2014), Barquet et al. (2018), Carmichael et al. (2018), Galford et al. (2016), Gerkensmeier and Ratter (2018a), Leitch et al. (2019), Maskrey et al. (2016), Muir et al. (2014), Ronco et al. (2015),
4. Use of interactive models/scenarios	9	Becu et al. (2017), Boeraeve et al. (2018), Gerkensmeier and Ratter (2018a), Minano et al. (2018), Mitter et al. (2014), Gerger Swartling et al. (2019) Söderholm et al. (2018), Van den Ven et al. (2016), Verkerk et al. (2017)
5. Use of knowledge brokers/intermediaries	4	Galford et al. (2016), Mitter et al. (2014), Robinson et al. (2016), Gerger Swartling et al. (2019),
6. No opportunities or enabling factors stated	8	Bitsura-Meszaros et al. (2019), Jacobs et al. (2018), Penning-Rowsell et al. (2014), Prutsch et al. (2018), Riddell et al. (2019), Rodriguez et al. (2014), Singh-Peterson et al. (2016), Sorensen et al. (2016)

Stakeholder group composition (cf. **category 1**) can have a role in improving adaptation planning and may address stakeholder resistance to it according to Gruber et al. (2017, p.17): “We have found that it is critical to bring together a broad and diverse group of stakeholders including community leaders, scientists, engineers, policy makers /…./ in order to effectively assess the situation and confirm the need to initiate adaptation planning”. Pasquier et al., (2020) attribute a successful co-production because of a good representation of stakeholders with high interests.

Another example of opportunities for increased **legitimacy** (cf. **category 2**) and **validation** of model results (cf. **category 3**) are identified by Muir et al., (2014, p.9): ”project found that a participatory approach to adaptation to coastal change allowed for increased amounts of information to be brought into the adaptation process and the integration of local knowledge into the decision-making process”, and according to Barquet et al., (2018, p.2010): “it created a stronger bond between the researchers involved in the project and the stakeholders participating in it, and increased reciprocity in the project so that stakeholders felt that they also benefitted from the project and not only contributed to it”. Boeraeve et al. (2018, p.27) identify the importance of **transparency** in the process and states that a clear aim and methods create a better understanding for the process. One enabling factor for transparency in this study of ecosystem services was a field trip with stakeholders, “one of the cases organized a field trip to bring participants with variable understanding of the area and the relevant issue to a more common level”. Gerger Swartling et al. (2019) point to the value of field trips, retreats and social events for offering “permissive spaces for informal networking, knowledge exchange and co-production” (Gerger Swartling et al. 2019, p.103).

Using **interactive models and simulations** has been shown to facilitate the discussions of risks with stakeholders by combining observation and with their help, validate the model results (cf. **category 4**) (Becu et al. 2017; Mitter et al. 2014). Engaging stakeholders such as local decision-makers with e.g. simulations, can increase the trust in the process or project and thus improve legitimacy (Gerkensmeier and Ratter 2018b; Gruber et al. 2017; Leitch et al. 2019).

Another enabling factor that is identified by Galford et al. (2016) and Robinson et al. (2016), is the use of **knowledge brokers** (cf. **category 5**). They describe the role of knowledge brokers as someone that can span over boundaries and gain better access to stakeholders, keep up the momentum by continuous communication and support an iterative process.

Policy discourse

Below we present examples of current practical application of co-production principles at local, regional and/or national level and potential problems identified.

Recent international **policy discourses** and implementations have, as has been previously noted, reflected a **long-term focus on stakeholder and actor inclusion in decision making and strategy processes.** Indeed, with the development and subsequent implementation of the UN Sustainable Development Goals (**SDGs**), the importance of **cooperation** and **partnership** in the overarching SDG goal 17, "Partnerships for the Goals", speaks concretely about **improving domestic capacities and multi-stakeholder partnerships.** That said, **much remains** in terms of understanding the potential for **strengthening adaptational capacities** through learning from the multiple ways people assess, analyze and understand their surroundings and the processes in them.

The **EU Strategy from 2013** on Adaptation to Climate Change (European Commission 2013) has as a clear ambition to secure a more climate resilient Europe. It focused on the **three objectives:** of promoting **proactive** action from Member States, of the '**climate-proofing**' of actions at the EU level, and of ensuring that decision-making is based on **salient, credible** and **reliable** information and knowledge. The strategy was **evaluated** in 2018 based in part on a public consultation scheme that ran from December 2017 through March 2018. The strategy primarily focusses on outlining adaptation goals and only to a lesser extent speaks to methodological aspects. As has been described in the section on the scientific discourse of this chapter, the focus has been on more interactive, co-produced knowledge increases saliency and credibility, and ensures better potential for acceptance and thus implementation. In today's political climate of counter-movements to climate change policies, **inclusion** and **participation** of **practitioners** is perceived of as **essential**, and in this section we will describe through examples **how co-production methodologies are present in policy discourses**, including how the institutionalized standard of public hearings adhere (or not) to principles of co-production. Importantly, the difference between being heard as a stakeholder/ interested party with an **opinion** and being a **part of** the very knowledge production process, which lays the primary foundation for policy making, **matters**. Examples of the former are plentiful, both in terms of adaptation processes (Söderholm, K. et al 2017; Champalle, C., Ford, J., & Sherman, M. (2015; Mitter, H., Kirchner, M., Schmid, E., & Schönhart, M. 2013) and other policy areas such as resource management and environmental policies, to mention but a few (e.g. Dale et al. 2018; Bjørkan & Veland 2019). The before mentioned methodological principles of co-production, however, moves the pole beyond the mere right to be heard - to a stronger focus on the inclusion of multiple types of knowledge in the process of knowledge production itself; a principle in effect strengthening the potential for a more democratized process where power is more broadly dispersed.

A **pivotal document** on climate change adaptation policy at the **European level** is the 2013 European Environmental Agency (**EEA**) report '**Adaptation in Europe**' (Isoard & inograd 2013). Here, though no concrete co-production **participatory approaches is promoted**, it includes a **call for methods and guidance** on how to best involve stakeholders in policy development. The report outlines the need for integration of multiple levels of governance, and for participatory, 'bottom-up'-approaches to planning and implementation of adaptation actions. However, when it comes to the co-produced identification of knowledge that supports what adaptation choices are made, the report is **limited** to addressing the need for further guidance on how to best involve stakeholders in more **general terms**.

The report does support, though, the rationale behind the Unchain approach, arguing for a focus on impact chains in climate change adaptation policies **and** the need for a focus on learning processes between government, research, business and civil society; a space identified where co-production of knowledge principles are salient.

Also, with regard to EU R&D strategies and outcome of recent **EU-financed research** concerning climate change adaptation, the matter of **inclusion of multiple actor-perspectives** has taken hold (ARCH 2019); RESIN 2018; Kingston & Cavan 2011). And as summarized in one of the reports from one project focusing on the transformation of climate data into services applicable in society (CLIMATEUROPE 2017), the need to **customize services benefiting adaptation capabilities** is best catered when **combining** new scientific knowledge with other forms of knowledge and understanding, and how this combination may be regarded as 'useful' in terms of adaptation. This means there are indeed notable exceptions from the general tendency that co-production efforts thus far have remained in the realm of scientific/ academic testing/ assessment, and not entered management or government to the degree argued for by co-production advocates (Prutsch et al 2014). One example worth mentioning is the development of a web-based **GIS** system for enhancing public involvement in both planning and decision making with regards to adaptational capacity and resilience to increased precipitation ad temperature rise in cities (Kingston & Cavan 2011). The tool developed is clearly meant to empower stakeholders in their adaptation efforts across Europe, but its impact is difficult to assess, as its website (www.grabs-eu.org) is currently offline, symbolizing perhaps one of the many challenges to implementation that exists, which is that once a project is finished and its tool presented, the responsibility to implement might crumble. Another example of a large-scale adaptation effort focusing on stakeholder participation is the **Climate-ADAPT partnership**, who's website sports a wholesome database (https://climate-adapt.eea.europa.eu/) where 1700 hits from a boolean search on keywords 'participation AND adaptation' indicates a focus on the importance of including multiple stakeholders in addressing adaptation issues. In parallel with EU strategies focusing on adaptational strategies and a social science focus on co-production methodologies, we see examples that indeed shows that implementation takes places on both national and regional levels.

Conclusions

The aim of **chapter 3** has been to **explore the role of knowledge co-production in climate change risk assessment to better inform adaptation decision-making and action**. An additional aim was to **identify challenges and knowledge gaps related to "user interface and stakeholder involvement" in relation to the impact chain (IC) model**.

To this end, we adopted a systematic review approach, modified to fit the scope of this study. Given the inclusion criteria specified for the review, we have analysed 39 articles, representing 19 of 36 countries in the OECD, that in one way or another involve stakeholder in different types of assessments of climate risks, impacts, vulnerability and/or adaptation. The objectives of the assessments varied from increasing knowledge about the consequences of climate change to local communities or specific sectors, to informing adaptation planning. Also, a number of studies aimed at developing methods and tools in relation to climate change and disaster risk management (see e.g. Hovelsrud et al. 2018). The rationale or underlying motive to why stakeholders were involved in these studies varied. Most studies referred to what Bremer and Meisch (2017) term as the 'iterative interactive lens', 'the institutional lens' and 'the extended science lens' – for example by contributing with local expertise and knowledge, trust building etc.

Even though l**ess than half** of the studies describe whether and how the **knowledge co-production process was evaluated**, several **lessons learned** can be drawn regarding **challenges** and **opportunities** to knowledge co-production in relation to climate change risk assessments. These factors are also identified in related literature (e.g. Harvey et al. 2019; Lang et al. 2012). **Most cases** in this review allude to the **challenges of stakeholder representation**, and **scale and scope of projects** in relation to decision-making contexts. **Other** challenges are **differing perspectives and understandings** of the **problem definition**, **communication**, and **legitimacy** of the climate information. Among the **enabling** factors, the **role of knowledge** brokers and **intermediaries** is highlighted (c.f. Dannevig and Aall 2015; Kirchhoff et al. 2015; Mitchell and Leach 2019) as well as the use of i**nteractive models and scenarios**. **Other** factors relate to the **stakeholder group composition,** which clearly indicates the importance of investing resources in identifying and ensuring that all relevant stakeholders are represented and able to participate (c.f. Harvey et al. 2019). Lastly, the opportunity to **validate model results** seemed to increase the legitimacy of the information and also informing adaptation planning processes.

Moreover, we see **few if any** indications or clear results as regards to the role of **knowledge co-production to inform adaptation decision-making**. Hence, there is a clear **gap** and a need for further research illustrating important **factors** concerning **how knowledge co-production processes can lead to actual adaptation action** (c.f. Hegger et al. 2012; Norström et al. 2020). On the same note, Wiek et al (2014, p.130) concludes that "there is little empirical evidence to what extent and through what features participation is leading to the desired societal effects and which effects exactly". The authors suggest that both tangible and less tangible effects ought to be captured.

At the same time, it has been shown in other cases that – in relation to **agenda setting** – **municipalities collaborating with academia** has a **positive** impact with respect to that of facilitating local adaptation processes (Dannevig et al. 2013). We also know that stakeholders at different ends of the 'adaptation learning cycle' (PROVIA 2013) have different needs and capacities to engage in participatory processes (André et al. 2020), which also is likely to have an impact on the scope and outcomes of such a process. In this review we have not looked into these specific aspects. However, **relating the challenges and opportunities to the differing case-specific contexts** is something that possibly could bring further clarity to what works when and how (see e.g. Harvey et al. 2019; Lang et al. 2012; Norström et al. 2020), and is thus an interesting aspect to explore in **future research** and to consider specifically when conducting the Unchain case studies.

Moreover, there is an ongoing debate and an acknowledged challenge in the wider transdisciplinary research community on how to **evaluate** the **effectiveness of transdisciplinary research** and how to **link** knowledge **co-production** processes with **societal change** (Hansson and Polk 2018). In addition to the often-cited criteria of **credibility**, **saliency** and **legitimacy** (Cash et al. 2003), Hansson and Polk (2018) highlight the importance (and difficulties) of also taking into account **external dynamics** related to the process. For example, even though the process is assessed as being successful from a project perspective (or logic), there may be other (societal) and contextual factors that also needs to be taken into consideration in the evaluation (see also Gerger Swartling et al. 2019).

To **conclude**, like other studies we see a **lack of reflection and transparency** as regards to **stakeholder involvement** in knowledge co-production and participatory processes. We also see the **need to critically reflect** on and be clear about **stakeholder roles** in the process as well as **expected outcomes** (cf. Cvitanovic et al. 2019). This is **key** to enable **better follow-up** and **comparison** between cases which can lead to **improvement** and **enhanced learning.** Thus, in the Unchain case studies it will be important to carefully consider how these aspects can be captured throughout the different phases of the project. Moreover, in addition to the specified research question of how knowledge co-production can, in a systematic way best, be integrated in the current Impact Chain framework we also see that the research question specified for this knowledge review – the role of knowledge co-production in climate change risk assessments to better inform decision-making and adaptation action – is still of relevance for the project and should be considered when designing and conducting the case studies.

References

PROVIA. (2013). Guidance on Assessing Vulnerability, Impacts and Adaptation to Climate Change.

André, K., Järnberg, L. and Gerger Swartling, Å. (2020). Co-Designing Climate Services to Support Adaptation to Natural Hazards in Two Swedish Municipalities. Stockholm Environment Institute, Stockholm, Sweden

ARCH. (2019). ARCH D3.1 Guideline on ARCH co-creation approach.

Barquet, K., Dickin, S. K., Meijer, J. J. and Dastgheib, A. (2018). Testing RISC-KIT's integrated approach for assessing Disaster Risk Reduction measures on the coast of Kristianstad, Sweden. Coastal Engineering, 134. 203–11.

Barry, A., Born, G. and Weszkalnys, G. (2008). Logics of interdisciplinarity. Economy and Society, 37(1). 20–49.

Becu, N., Amalric, M., Anselme, B., Beck, E., Bertin, X., et al. (2017). Participatory simulation to foster social learning on coastal flooding prevention. Environmental Modelling and Software, 98. 1–11.

Bitsura-Meszaros, K., Seekamp, E., Davenport, M. and Smith, J. W. (2019). A PGIS-Based Climate Change Risk Assessment Process for Outdoor Recreation and Tourism Dependent Communities. SUSTAINABILITY, 11(12). DOI: 10.3390/su11123300

Bjørkan, M., & Veland, S. (2019). Beyond concensus: Perceptions of risk from petroleum developments in Lofoten, Vesterålen and Senja, Norway. doi:10.1093/icesjms/tsz056

Blaikie, N. (2010). Designing social research (2nd ed.). Cambridge: Polity Press.

Boeraeve, F., Dufrene, M., De Vreese, R., Jacobs, S., Turkelboom, F., Verheyden, W., Pipart, N. and Dendoncker, N. (2018). Participatory identification and selection of ecosystem services: Building on field experiences. Ecology and Society, 23(2). 19p. DOI: 10.5751/ES-10087-230227

Boezeman, D., Vink, M., Leroy, P. and Halffman, W. (2014). Participation under a spell of instrumentalization? Reflections on action research in an entrenched climate adaptation policy process. Presented at the Critical policy studies, Great Britain. Taylor and Francis Group. https://ezp.sub.su.se/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsbl&AN=vdc.100032650642.0x000001&site=eds-live&scope=site

Bracken, L. J., Oughton, E. A., Donaldson, A., Cook, B., Forrester, J., Spray, C., Cinderby, S., Passmore, D. and Bissett, N. (2016). Flood risk management, an approach to managing cross-border hazards. Natural Hazards: Journal of the International Society for the Prevention and Mitigation of Natural Hazards, 82(2). 217. DOI: 10.1007/s11069-016-2284-2

Bremer, S. and Meisch, S. (2017). Co-production in climate change research: reviewing different perspectives. WILEY INTERDISCIPLINARY REVIEWS-CLIMATE CHANGE, 8(6). DOI: 10.1002/wcc.482

Brink, E., Wamsler, C., Adolfsson, M., Axelsson, M., Beery, T., et al. (2018). On the road to 'research municipalities': analysing transdisciplinarity in municipal ecosystem services and adaptation planning. Sustainability Science, 13(3). 765–84. DOI: 10.1007/s11625-017-0499-0

Carter, S., Steynor, A., Vincent, K., Visman, E., & Waagasæther, K. (2018). Co-Production in African weather and climate services. Wiser/ UKAid/NERC Science of the Environment

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jäger, J. and Mitchell, R. B. (2003). Knowledge systems for sustainable development. Proceedings of the National Academy of Sciences of the United States of America, 100(14). 8086–91.

Champalle, C., Ford, J., & Sherman, M. (2015). Prioritizing Climate Change Adaptations in Canadian Arctic Communities. Sustainability, 7(7), 9268-9292. doi:10.3390/su7079268

Climateurope. (2017). EUROPEAN CLIMATE OBSERVATIONS, MONITORING AND SERVICES INITIATIVE DELIVERABLE D4.2, Lessons and practice of co-developing Climate services with users

Cvitanovic, C., Howden, M., Colvin, R. M., Norström, A., Meadow, A. M. and Addison, P. F. E. (2019). Maximising the benefits of participatory climate adaptation research by understanding and managing the associated challenges and risks. Environmental Science & Policy, 94. 20–31. DOI: 10.1016/j.envsci.2018.12.028

Dale, B., Veland, S., & Hansen, A. M. (2018). Petroleum as a Challenge to Arctic Societies: Ontological Security and the oil-driven 'push to the north'. Journal of Extractive Industries and Society. doi: https://doi.org/10.1016/j.exis.2018.10.002;

Dannevig, H. and Aall, C. (2015). The regional level as boundary organization? An analysis of climate change adaptation governance in Norway. Environmental Science & Policy, 54. 168–75. DOI: 10.1016/j.envsci.2015.07.001

Dannevig, H., Hovelsrud, G. K. and Husabø, I. A. (2013). Driving the Agenda for Climate Change Adaptation in Norwegian Municipalities: Environment and Planning C: Government and Policy. DOI: 10.1068/c1152

Dawkins, E., André, K., Axelsson, K., Benoist, L., Swartling, Å. G. and Persson, Å. (2019). Advancing sustainable consumption at the local government level: A literature review. Journal of Cleaner Production, 231. 1450–62. DOI: 10.1016/j.jclepro.2019.05.176

Easterby-Smith, M., Thorpe, R., & Jackson, P. R. (2008). Management research (3rd ed.). London: Sage.

EEA (2013). Adaptation in Europe - Addressing Risks and Opportunities from Climate Change in the Context of Socio-Economic Developments. EEA R. Publications Office of the European Union, 2013, Luxembourg. https://www.eea.europa.eu/publications/adaptation-in-europe

Ernst, K. M., Swartling, Å. G., André, K., Preston, B. L. and Klein, R. J. T. (2019). Identifying climate service production constraints to adaptation decision-making in Sweden. Environmental Science & Policy, 93. 83–91. DOI: 10.1016/j.envsci.2018.11.023

Fatorić, S. and Seekamp, E. (2019). Knowledge co-production in climate adaptation planning of archaeological sites. Journal of Coastal Conservation, 23(3). 689–98. DOI: 10.1007/s11852-019-00698-8

Field, C. B., Barros, V. R. and IPCC, eds. (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY

Galford, G. L., Nash, J., Betts, A. K., Carlson, S., Ford, S., et al. (2016). Bridging the climate information gap: a framework for engaging knowledge brokers and decision makers in state climate assessments. Climatic

Change: An Interdisciplinary, International Journal Devoted to the Description, Causes and Implications of Climatic Change, 138(3–4). 383. DOI: 10.1007/s10584-016-1756-4

Gerger Swartling, Å., Tenggren, S., Andre, K. and Olsson, O. (2019). Joint knowledge production for improved climate services: Insights from the Swedish forestry sector. Environmental Policy and Governance, 29(2). 97–106. DOI: 10.1002/eet.1833

Gerkensmeier, B. and Ratter, B. M. W. (2018a). Multi-risk, multi-scale and multi-stakeholder – the contribution of a bow-tie analysis for risk management in the trilateral Wadden Sea Region. Journal of Coastal Conservation: Planning and Management, 22(1). 145. DOI: 10.1007/s11852-016-0454-8

Gerkensmeier, B. and Ratter, B. M. W. (2018b). Governing coastal risks as a social process—Facilitating integrative risk management by enhanced multi-stakeholder collaboration. Environmental Science and Policy, 80. 144–51.

Glaas, E. and Jonsson, A. C. (2014). Facilitating cross-sectoral assessments of local climate change vulnerability. International Journal of Urban Sustainable Development, 6(2). 174–89.

Gruber, J. S., Rhoades, J. L., Simpson, M., Stack, L., Yetka, L. and Wood, R. (2017). Enhancing climate change adaptation: strategies for community engagement and university-community partnerships. Journal of Environmental Studies and Sciences, 7(1). 10. DOI: 10.1007/s13412-015-0232-1

Haddaway, N. R., Macura, B., Whaley, P. and Pullin, A. S. (2017). ROSES flow diagram for systematic reviews. Version 1.0. , 2017. DOI: 10.6084/m9.figshare.5897389.v3

Haddaway, N. r., Woodcock, P., Macura, B. and Collins, A. (2015). Making literature reviews more reliable through application of lessons from systematic reviews. Conservation Biology, 29(6). 1596–1605. DOI: 10.1111/cobi.12541

Hansson, S. and Polk, M. (2018). Assessing the impact of transdisciplinary research: The usefulness of relevance, credibility, and legitimacy for understanding the link between process and impact. Research Evaluation, 27(2). 132–44. DOI: 10.1093/reseval/rvy004

Harvey, B., Cochrane, L. and Epp, M. V. (2019). Charting knowledge co-production pathways in climate and development. Environmental Policy and Governance, 29(2). 107–17. DOI: 10.1002/eet.1834

Hegger, D. and Dieperink, C. (2014). Toward successful joint knowledge production for climate change adaptation : lessons from six regional projects in the Netherlands. Ecology and Society, 19(2). https://ezp.sub.su.se/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsjsr&AN=edsjsr.26269545&site=eds-live&scope=site

Hegger, D., Lamers, M., Zeijl-Rozema, A. V. and Dieperink, C. (2012). Conceptualising joint knowledge production in regional climate change adaptation projects: Success conditions and levers for action. Environmental Science and Policy, 18. 52–65.

Hewitt, C. D., Stone, R. C. and Tait, A. B. (2017). Improving the use of climate information in decision-making. Nature Climate Change, 7. 614–16. DOI: 10.1038/nclimate3378

Hovelsrud, G. K., Karlsson, M. and Olsen, J. (2018). Prepared and flexible: Local adaptation strategies for avalanche risk. Cogent Social Sciences, 4(1). 1460899. DOI: 10.1080/23311886.2018.1460899

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. R.K. Pachauri and L.A. Meyer (ed.). IPCC, Geneva, Switzerland

Isoard, S., & Winograd, M. (2013). Adaptation in Europe: Addressing risks and opportunities from climate change in the context of socio-economic developments.

Jasanoff, S. (2004). States of Knowledge: The Co-Production of Science and the Social Order. Routledge

Kingston, R. and Cavan, G. (2011). GRaBS Assessment Tool User Guidance. Centre for Urban and Regional Ecology School of Environment & Development University of Manchester

Kirchhoff, C. J., Lemos, M. C. and Kalafatis, S. (2015). Narrowing the gap between climate science and adaptation action: The role of boundary chains. Climate Risk Management, 9. 1–5.

Klein, R. J. T. and Juhola, S. (2014). A framework for Nordic actor-oriented climate adaptation research. Environmental Science & Policy, 40. 101–15. DOI: 10.1016/j.envsci.2014.01.011

Lang, D. J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M. and Thomas, C. J. (2012). Transdisciplinary research in sustainability science: practice, principles, and challenges. Sustainability Science, 7(1). 25. DOI: 10.1007/s11625-011-0149-x

Leitch, A. M., Palutikof, J. P., Rissik, D., Boulter, S. L., Tonmoy, F. N., Webb, S., Vidaurre, A. C. P. and Campbell, M. C. (2019). Co-development of a climate change decision support framework through engagement with stakeholders. Climatic Change: An Interdisciplinary, International Journal Devoted to the Description, Causes and Implications of Climatic Change, 153(4). 587. DOI: 10.1007/s10584-019-02401-0

Mastrandrea, M. D., Heller, N. E., Root, T. L. and Schneider, S. H. (2010). Bridging the gap: linking climate-impacts research with adaptation planning and management. Climatic Change, 100(1). 87–101.

McNie, E. C. (2007). Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environmental Science & Policy, 10(1). 17–38.

McClure, A. (2018). Learning within & about climate science. What has transdisciplinary engagement through FRACTAL taught us? FRACTAL Briefing note.

Miller, C. A. and Wyborn, C. (2018). Co-production in global sustainability: Histories and theories. Environmental Science & Policy. DOI: 10.1016/j.envsci.2018.01.016

Mitchell, R. E. and Leach, B. (2019). Knowledge coproduction in environmental impact assessment: Lessons from the mining industry in Panama. Environmental Policy and Governance, 29(2). 87–96. DOI: 10.1002/eet.1832

Mitter, H., Kirchner, M., Schmid, E. and Schönhart, M. (2014). The participation of agricultural stakeholders in assessing regional vulnerability of cropland to soil water erosion in Austria. Regional Environmental Change, 14(1). 385. DOI: 10.1007/s10113-013-0506-7

Mobjörk, M. (2009). Crossing Boundaries: The Framing of Transdisciplinary Research. Report no. 64. Centre for Housing and Urban Research, Örebro University

Mobjörk, M. (2010). Consulting versus participatory transdisciplinarity: A refined classification of transdisciplinary research. Futures, 42(8). 866–73.

Muir, D., Dawson, A. G., Gagnon, A. S. and O'Mahony, C. (2014). Vulnerability and adaptation to extreme coastal flooding: An example from the south ford area, scottish outer hebrides. Coasts, Marine Structures and Breakwaters 2013: From Sea to Shore - Meeting the Challenges of the Sea Vol. 122–32. Proceedings of the Coasts, Marine Structures and Breakwaters 2013: From Sea to Shore - Meeting the Challenges of the Sea. ICE Publishing. DOI: 10.1680/fsts.59757.0022

Nakashima, D. J., Galloway McLean, K., Thulstrup, H. D., Ramos Castillo, A., & Rubis, J. T. (2012). Weathering Uncertainty: Traditional knowledge for climate change assessment and adaptation. UNESCO.

Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., et al. (2020). Principles for knowledge co-production in sustainability research. Nature Sustainability. 1–9. DOI: 10.1038/s41893-019-0448-2

Nowotny, H., Scott, P. and Gibbons, M. (2003). Introduction: 'Mode 2' Revisited: The New Production of Knowlegde. Minerva, 41(3). 179–94. DOI: 10.1023/A:1025505528250

Palutikof, J. P., Street, R. B. and Gardiner, E. P. (2019). Decision support platforms for climate change adaptation: an overview and introduction. Climatic Change, 153(4). 459–76. DOI: 10.1007/s10584-019-02445-2

Pasquier, U., Few, R., Goulden, M. C., Hooton, S., He, Y. and Hiscock, K. M. (2020). "We can't do it on our own!"—Integrating stakeholder and scientific knowledge of future flood risk to inform climate change adaptation planning in a coastal region. Environmental Science and Policy, 103. 50–57. DOI: 10.1016/j.envsci.2019.10.016

Potts, J. (2001). Knowledge and markets. Journal of Evolutionary Economics, 11(4). 413–31. DOI: 10.1007/PL00003865

PROVIA (2013). PROVIA Guidance on Assessing Vulnerability, Impacts and Adaptation to Climate Change. Consultation document. United Nations Environment Programme, Nairobi, Kenya

Prutsch, A., Felderer, A., Balas, M., König, M., Clar, C. and Steurer, R. (2014). Methods and Tools for Adaptation to Climate Change. A Handbook for Provinces, Regions and Cities. Environment Agency Austria, Wien. https://climate-adapt.eea.europa.eu/metadata/guidances/methods-and-tools-for-adaptation-to-climate-change-a-handbook-for-provinces-regions-and-cities

RESIN. (2018). Developing the RESIN tools, advancing local adaptation. Retrieved from

Riddell, G. A., van Delden, H., Maier, H. R. and Zecchin, A. C. (2019). Exploratory scenario analysis for disaster risk reduction: Considering alternative pathways in disaster risk assessment. International Journal of Disaster Risk Reduction, 39. https://ezp.sub.su.se/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselp&AN=S2212420919302286&site=eds-live&scope=site

Robinson, C. J., Maclean, K., Hill, R., Bock, E. and Rist, P. (2016). Participatory mapping to negotiate indigenous knowledge used to assess environmental risk. Sustainability Science, 11(1). 115. DOI: 10.1007/s11625-015-0292-x

Rodela, R. and Gerger Swartling, Å. (2019). Environmental governance in an increasingly complex world: Reflections on transdisciplinary collaborations for knowledge coproduction and learning. Environmental Policy and Governance, 29(2). 83–86. DOI: 10.1002/eet.1842

Rodriguez, D., Cox, H., deVoil, P. and Power, B. (2014). A participatory whole farm modelling approach to understand impacts and increase preparedness to climate change in Australia. Agricultural Systems, 126. 50–61.

Runhaar, H., Wilk, B., Persson, Å., Uittenbroek, C. and Wamsler, C. (2018). Mainstreaming climate adaptation: taking stock about "what works" from empirical research worldwide. Regional Environmental Change, 18(4). 1201–10.

Söderholm, K., Pihlajamäki, M., Dubrovin, T., Veijalainen, N., Vehviläinen, B., & Marttunen, M. (2017). Collaborative Planning in Adaptive Flood Risk Management under Climate Change. Water Resources Management, 32(4), 1383-1397. doi:10.1007/s11269-017-1875-3

Taylor, A., Scott, D., Steynor, A. and McLure, A. (2017). Transdisciplinarity, Co-Production, and Co-Exploration: Integrating Knowledge across Science Policy and Practice in FRACTAL. FRACTAL Working Paper 3. University of Cape Town, Cape Town, South Africa

Wiek, A., Talwar, S., O'Shea, M. and Robinson, J. (2014). Toward a methodological scheme for capturing societal effects of participatory sustainability research. Research Evaluation, 23(2). 117–32. DOI: 10.1093/reseval/rvt031

Yusuf, J. (Wie), St. John, I., Burton, Covi, M. and Nicula, J. G. (2018). Engaging Stakeholders in Planning for Sea Level Rise and Resilience. Journal of Contemporary Water Research & Education, 164(1). 112–23.

Socio-economic scenarios and societal exposure to climate change

Introduction

Climate change is a cross-cutting challenge. The temperatures increase and its many biological and physical consequences meet modern society with its economic, social and societal developments. Researchers try to better identify the risks this entails under different assumptions for either aspect of this challenge. This requires a **multi-faceted** approach of which the foundations have been laid out, but which still need to be built further. One contribution lies in the development of a framework to **integrate socioeconomic scenarios into the impact chain-based risk analysis**. While the **former** approach is based on **main narratives about the future population, their needs, their way of trading and cooperating with each other**, the **latter** approach aims at the **integration of current state vulnerability, exposure and hazard assessment into meaningful risk indicators**. **Combining** both approaches is a **new research territory**. However, to contribute to this integrated view, we need to briefly **outline work done in the development and description of socioeconomic pathways**, their relation to **economic impact assessment of climate change**, the use of the **impact chain approach in socioeconomic analyses** and **vice versa**. Thus, the literature review tries to answer the following **questions**:

- Which **socioeconomic pathways** are currently used and described in the literature?
- What are the **results** obtained from **economic modelling** addressing these scenarios?
- What are the experiences in first attempts c**ombining economic scenario analyses with the impact chain approach**?

This review seeks to understand the value of using **socioeconomic scenarios** to i**mprove climate impact assessment** at scale, and to **translate** the results of climate impact studies for **policy formulation** and **decision-makin**g.

Method

Drawing on the extensive literature review methodology applied in chapter 2 methodology, and the findings presented in chapter 2, we have identified for this chapter **five** broad **research challenges** are generally associated with recent implementations of climate change impact chains; namely challenges related to model design, identification of system elements and interrelations, data availability and reliability, selective perspectives, biases or lack of better knowledge and experiences, and challenges related to keeping it clear and transparent.

Based on the respective contributions in this chapter, the selection of literature to be included started out with a list of approximately 20 publications which are mostly associated with discussions of "Challenges related to model design", "Challenges related to the identification of system elements and interrelations", and, "Challenges related to data availability and reliability". However, as the selection of literature was not explicitly intended to consider socioeconomic scenarios, only some of these initially selected publications did deal with assessments of socio-economic impacts of climate change (Bachner et al. 2015; Steininger et al. 2016). A key objective for this chapter was, therefore, to supplement these preliminary findings with an additional overview of the current state of research in the quantification of socio-economic scenario projections.

Our initial list has therefore been merged with respective prior own thematic expertise (see e.g. Lutz et al. 2019) and further insights from an **additional** literature research. For this literature research, the following **criteria** were defined as essential selection criteria for consideration in this overview:

- Publications considering the availability and usefulness of selected applications of **socio-economic scenarios** in adaptation policy planning.
- Publications dealing with the **quantification of socio-economic pathways** (applications of indicators to map relevant impacts, exposure and resulting risks).
- **Dynamic modelling** studies which derive projections of social exposure and vulnerability from expected futures developments of **key socio-economic indicators** (such as expected population dynamics, anticipated future investment needs, long-rung income trends and price dynamics, consumer spending on different goods and services, ...)
- **Methodological** discussions of **key socio-economic scenario element projections**. Examples are robustness of applied indicator metrics; performance of single-sector models compared to integrated multi-sector models; opportunities for better integration of regional aspects/to downscale existing national socio-economic scenarios in adaptation assessments; mapping of key climate-economy re-enforcing loops such as rural land use allocation patterns, etc.

Overall, more than 70 publications have been evaluated for this chapter. As before, only publications from a climate change vulnerability context have been considered. However, in line with the pre-identified knowledge gaps (but in contrast to the earlier chapter 2 literature review), we decided not to limit this overview exclusively to publications with concrete reference to the Impact Chain methodology. As this approach identified the extensive literature on **Shared Socioeconomic Pathways** (SSPs) as an essential reference for the current state of research on internationally harmonized scenario projections, the following section provides a self-contained introduction to this literature. Subsequently, chapter 4 provides an overview on recent applications of economic modelling in the closer context of the Impact Chain methodology.

Socioeconomic development under climate change

Overview

Climate change is known to be anthropogenically forced and has impacts on both biophysical and socioeconomic systems (Kalaugher et al. 2013). The effects of human activities on climate depend on future emissions of greenhouse gases, and the impacts of the resulting changes in climate are likely to occur in a longer time period, stretching from decade to centuries depending on the future state of the world (Berkhout & van Drunen 2007). To understand these future changes, the Intergovernmental Panel on Climate Change (IPCC) developed the **representative concentration pathways** (RCPs[3]) for global atmospheric radiative forcing connected to levels of GHG emissions and concentrations until 2100, which are used to drive climate models to determine the impacts of climate change. Although the emission scenarios were linked to a set of assumptions about future population totals, economic development and land use change, they were constructed with **little**

[3] The RCPs are named after the change in radiative forcing (RCP2.6, RCP4.5, RCP6.0 and RCP8.5), RCP2.6 means, for example, that radiative forcing will increase by 2.6 W/m^2 by 2100 compared to the pre-industrial situation.

consideration to changes in the worlds' socioeconomic and demographics which are expected to impact climate change (Arnell et al. 2004). Economic growth, changes in demographics, technology, governance, lifestyles among others influence the vulnerability of different groups of people to the impacts of climate change. Consequently, the need to increase capacities for adaptation and thus reducing the risk exposure of society has become imperative. On this basis, it is **inappropriate** to assume that **the future resembles the present**, as earlier climate impact studies did. Therefore, there is need for **socioeconomic scenarios** to evaluate how future climatic change will affect social and economic systems, thereby informing both climate adaptation and mitigation research and policymaking (Berkhout, Hertin & Jordan 2002).

The challenges of scenario building

Berkhout, Hertin & Jordan (2002) have identified what they denote as **four irreducible challenges** embedded in that of trying to **project social and economic futures**: (1) the dangers of **reductionism**; (2) **rapid innovation** and **discontinuity**; (3) **reflexivity**; and (4) the problem of **framing**.

Firstly, the authors posit that social systems are difficult to project because of the **unpredictable nature of human behaviour**. As a result, **reductionist** approaches to analyse socioeconomic systems are less successful in replicating reality. However, the authors mention that modelling some aspects of social change for long-term predictions could be done with high certainty (for example, population and mortality trends). Other aspects, such as economic growth and inflation for example, are more difficult to predict, even when powerful models and quality historical data are used. Still others, such as political and cultural change, are not at all predictable by models.

Second, unlike natural systems where well-founded assumptions of continuity and universality can be formed and tested, **social and economic systems** are **generative** and do **not allow such universal assumptions**. Although over short periods of time many important structures, processes and attitudes are stable, over longer periods of time we are aware that social and economic relationships change, and that institutional and technological innovations profoundly modify incentives, behaviours and social structures. Usually these processes of change are unexpected and poorly understood by participants, even as they occur.

The **third** challenge is **reflexivity**. We are aware that the future can be shaped by the past. Since people are **ignorant** about some aspects of the **future** of social and economic systems, they try to anticipate the future by bringing into reality the **past**. More so, humans orient change towards more **desired outcomes** and away from those less desired and try to adapt towards emergent realities. The more widely a **desirable** vision of the future is shared by social actors, the more **likely** it is to be brought into reality. However, there are several instances where widely shared visions failed to become reality, demonstrating further how **uncertain** future social systems prediction could be.

Finally, the **fourth** challenge is related to differences in **framing knowledge**. Since the opinions about what the future holds are diverse, so is the **prediction** of future social systems highly **contested** by different groups of people. This results in **conflicting expectations of the future** as often seen in climate change policy debates. In talking about social and economic futures it is therefore **extremely difficult** to separate the **analytical** from the **normative**. All pictures of the future are therefore likely to be coloured by reactions of preference or rejection. Analysts of social and economic futures must, therefore, **account for the variety of ways in which 'the future' is framed**.

Ways of addressing the challenges of scenario building

These **inter-related problems** of reductionism, discontinuity, reflexivity and framing pose an **immense challenge** for the prediction of socioeconomic systems, and by extension to climate impact assessment. And it is important to note that these challenges are addressed very differently in individual scenario development processes. Berkhout, Hertin & Jordan (2002) identified **three main approaches** in this regard: (1) **Extrapolatory** approaches, (2) **normative** approaches, and (3) **exploratory** approaches.

Extrapolatory approaches are based on forecasting techniques which rely on past observations to predict the future. The **extrapolatory** approach assumes the future as a **continuation of the past** and assumes **time-invariant relationships** between observed variables. Such an approach is apparently always appropriate as long as the relationships observed in the past will **not change** (significantly) in the future. However, for **long term scenarios** which assume, for example, far-reaching technological innovations or comprehensive changes in income and expenditure structures on a global scale, such assumption **cannot** be maintained.

Normative procedures simplify the task of projecting future socioeconomic development in that they do **not** intend to **reflect actual human behaviour**. By simply defining future social developments, such an approach obviously facilitates the planning of long-term reduction or adaptation measures tremendously. To the same extent, however, it is also subject to **fundamental misjudgement** risks as human behaviour is, among other things, subject to preferences, available information and prevailing future expectations which will usually vary over time. Usually, the developments resulting from the social interaction of these influencing factors are not oriented towards normative objectives.

Exploratory approaches focus on **creating alternative future**s by capturing a variety of socioeconomic conditions outside the control of humans and clearly emphasis on the ability of humans to adapt to changing future circumstances. Current practices of scenario development including the SSPs tend to stress on exploratory approaches because of its **ability to respond to the weaknesses of the other two approaches**.

Addressing uncertainties in scenario-building

Scenarios need to address **uncertainty**. Berkhout, Hertin & Jordan (2002) identify **three** approaches to scenario development and dealing with uncertainty within respectively (1) **extrapolation** approaches, (2) **normative** approaches, and (3) **exploratory** approaches.

The **former** relies on **past trends** to **predict the future**. This approach assumes the future as a continuation of the past and therefore use **mathematical** principles to establish a **rigorous** relationship between variables in global models (Forrester 1973). However, the method does **not** consider **innovations** that are likely to cause changes in these relationships.

Second, the **normative** approach explores positive and negative **actions** and **decisions** of humans that is likely to **affect the future** (Dreborg 1996). While this approach has the potential for objective planning that creates a desired future, it has the tendency to either **over-** or **underestimate** the **influence of humans in the future**.

Third, the **exploratory** approaches focus on creating alternative futures by capturing a **variety** of socioeconomic conditions **outside the control of humans** and clearly emphasis on the ability of humans to adapt to changing future circumstances. This approach also considers the **value of**

innovation to cause changes in the future. **Current practices** of scenario development tend to stress on **exploratory** approaches because of its ability to respond to the weaknesses of the other two approaches.

According to Parson et al. (2006), to develop scenarios for climate impact assessment requires many important choices including the representation of uncertainties to create **alternative scenarios**. In this regard, the role of **socioeconomic factors** in addressing climate change remains **essential**. The authors argue that the simple linear pathway extending from the socioeconomic determinants of greenhouse-gas emissions which affect the composition of the atmosphere and climate, resulting in direct and indirect impacts of climate change **does not represent the complete structure of the climate issue**, which has many linkages and feedbacks.

From climate variables to SRES to SSPs

Climate change risk is the product of **three** interacting elements: **Climatic hazards**, **exposure**, and **vulnerability** (IPCC 2014a). While these three elements are all subject to change over time, many **early climate research activities** have **concentrated** on the first one, the **climate hazard**s, identifying, understanding, quantifying and modelling different aspects of these hazards.

By mid-1990s, the Special Report on Emissions Scenarios (SRES), (IPCC 2000), published a set of scenarios, termed as the **SRES scenarios** (see Nakićenović et al. 2000). These scenarios contain **four narratives** that describe the evolution of the world's **population**, **economies** and **political** structure over the next decades, resulting in **six scenarios** used as **inputs to climate models**. Starting **2011**, a new set of **socioeconomic scenarios** was developed as part of the IPCC's 5th Assessment Report on climate policy issues. Kriegler et al. (2012) describe what motivated this activity. Ebi et al. (2014) describe the further development process towards the final Shared Socioeconomic Pathways (SSPs). These **SSPs** represent the **current state of the art of socioeconomic scenarios** in integrated assessment models

The **SSPs** for climate impact assessment follow the so-called **forward** and **inverse** methods. The **forward** method selects and combines a number of **socioeconomic factors** into a set of **probable pathways** that shows the different directions in which the **world may evolve**. A similar approach is used for the SRES scenarios (Nakićenović et al. 2000) and the Millennium Ecosystem Assessment (Bennett et al. 2005). The **inverse** method starts from the point of a **future** climate outcome. It then identifies a combination of **socioeconomic factors** that are **likely to produce certain desirable outcomes**. Examples can be found in the scenarios for achieving sustainable energy transitions (Riahi et al. 2012), global sustainability (Raskin et al. 1998), and other specific climate goals (Toth 2003). However, both **methods** are **complementary** and contribute to the formulation of the SSPs.

The **SSPs** thus are a joint effort of the international scientific community and describe plausible global developments that will lead to different challenges for climate change mitigation and adaptation in the future. They are based on **five narratives** that describe **alternative socioeconomic developments.** The long-term demographic and economic projections of the SSPs show a wide range of global futures. The narratives provide qualitative descriptions of developments in the areas of demographics, human development, economy and lifestyle, politics and institutions, technology, environment and natural resources (O'Neill et al. 2017). Together, the five narratives of the SSPs cover a wide range of socioeconomic developments. It turns out that only certain combinations of RCPs and SSPs can be realized at certain CO_2 prices, with the highest level of mitigation it is not possible with two of the scenarios (regional rivalry and fossil fuel development), even under high CO_2 price. The authors themselves point out that non-achievement in the model does not mean that it is impossible (Riahi et al. 2017). Detailed results of many quantifications for all five SSPs with different IAMs can be found in the IIASA database (IIASA 2016). The narrative-based, socioeconomic scenarios can be **solidified** using **economic simulation models**. Population-wise SSP 1 and 5 are close to each other and together with SSP 3 define the projection range. In terms of GDP development, SSPs 3 and 5 form the lower and upper trajectories.

Figure 11 *Classification of the SSPs according to their socioeconomic challenges for mitigation and adaptation (O'Neill et al. 2017)*

Because of the **high degree of uncertainty** about future developments (see above), the **SSPs** represent **different global socioeconomic developments** for the 21st century. They are intended to cover policy-relevant scenario ranges. See O'Neill et al. (2014) for a self-contained introduction to the five SSP implementations.

The **SSPs** serve as a basis and as components for scenarios (IPCC 2014a) and are part of the broad range of possible socioeconomic trajectories into the future. On the one hand, they serve as a **basis** for deriving the **Representative Concentration Pathways** (RCPs) and, on the other hand, for **characterizing the challenges of adaptation and mitigation**. See van Vuuren et al. (2014) as a basic introduction to this RCP-SSP scenario framework.

Each **SSP scenario** is composed of a **narrative** or storyline and, in a first step, separate quantifications in different global models for **population** (IIASA (KC & Lutz 2017)), gross domestic product (**GDP**, separate implementations in separate models of IIASA (Crespo Cuaresma 2017), OECD (Dellink et al. 2017) and PIK (Leimbach et al. 2017)) and **urbanization** (NCAR (Jiang & O'Neill 2017)). Population development is a key driver of GDP growth. Furthermore, **additional variables** such as **energy consumption** and **land use** have been quantified on this basis in various **global Impact Assessment Models** (IAMs). **Based** on the **SSPs**, quantified **socioeconomic scenarios** can be developed which, which in combination with **RCP**-based climate projections can provide a starting point for the analysis of **climate impacts and policie**s (IPCC 2014a). See table below for an overview of factors covered qualitatively or quantitatively in the SSPs (Kriegler et al. 2012; O'Neill et al. 2014; Rozenberg et al. 2014; Schweizer & O'Neill 2014; van Vuuren et al. 2012). These factors interact to produce development pathways relevant for defining challenges to mitigation and adaptation.

***Table 6** Socioeconomic factors used for developing SSPs (Kriegler et al. 2012; O'Neill et al. 2014; Rozenberg et al. 2014; Schweizer & O'Neill 2014; van Vuuren et al. 2012)*

Factors	Scenario element
Demographics	Population total and age structure
	Urban vs. rural populations, and urban forms
	Other location information, such as coastal vs. inland
Economic development	Global and regional GDP, or trends in productivity
	Regional, national, and sub-national distribution of GDP, including economic catch-up by developing countries
	Sectoral structure of national economies, in particular the share of agriculture, and agricultural land productivity
	Share of the population in extreme poverty
	Nature of international trade
	Income
Welfare	Human development
	Educational attainment
	Health, including access to public health and health care infrastructure
Environmental and ecological factors	Air, water, soil quality
	Ecosystem functioning
Resources	Fossil fuel resources and renewable energy potentials Other key resources, such as phosphates, fresh water etc.
Institutions and governance	Existence, type and effectiveness of national/regional/global institutions
	Degree of participation
	Rule of law
Technological development	Type (e.g. slow, rapid, transformational) and direction (e.g. environmental, efficiency, productivity improving) of technological progress
	Diffusion of innovation in particular sectors, e.g. energy supply, distribution and demand, industry, transport, agriculture
Broader societal factors	Attitudes to environment/sustainability/equity and world views
	Lifestyles (including diets)
	Societal tension and conflict levels
Policies	Non-climate policies including development policies, technology policies, urban planning and transportation policies, energy security policies, and environmental policies to protect air, soil and water quality.

For the **five SSPs** (SSP1–SSP5), **baseline** or reference developments show **very different** paths of **energy consumption** and **emissions** (Riahi et al. 2017). Depending on **climate change**, the **vulnerability** of the population, the **political intent** to **adapt** and the **financial possibilities** for adaptation the challenges for adaptation in the SSPs are **different**. **SSP 2** is in the middle of the socioeconomic challenges for climate mitigation and adaptation and often serves as a **reference scenario** in **economic simulations**. GHG mitigation scenarios extend the narrative to climate policy assumptions corresponding to the general philosophy of the five SSPs (Riahi et al. 2017). Thus, different climate protection efforts correspond to representative concentration pathways (RCPs).

It is important to understand the **purpose** of the **SSPs**. Generally, **socioeconomic scenarios** can be used in **three** different ways, namely as (1) **quantitative inputs** for **model-based assessment**, for (2) qualitative **assessments** of **climate change**, and (3) to support **communication** and raise **awareness** (Berkhout, Hertin & Jordan 2002).

Impact assessments reflect the interplay of socioeconomic effects **across different scales**. Furthermore, chapter 2 identifies a strong **local** or **regional** focus of the considered Impact Chain applications (with two thirds of all considered studies focusing on regional or local applications). Recently, a number of studies has addressed **downscaling** from global assumptions and estimates, with a primary focus on **quantifying metrics** that are typically broad and based on a consistent set of inputs and assumptions across countries (Frame et al. 2018; Leimbach et al. 2017). Po**pulation, productivity**, and **capital stock growth** are suggested to estimate **regional per capita GDP** (Dellink et al. 2017), or changes in **age structure**, **educational attainment**, and **economic growth** to project **national per capita income** (Crespo Cuaresma 2017). Therefore, allowing studies that build on the SSPs architecture to apply it at the regional scale (Alfieri et al. 2015; Carey 2014; Palazzo 2000), the national scale (König et al. 2015; UKCIP (UK Climate Impacts Programme) 2001) and the sub-national scale (Absar & Preston 2015; Nilsson et al. 2017).

Modelling adaptation

For a long time, studies on how to deal with global climate change focused on reducing greenhouse gas emissions. In comparison to studies dealing with the evaluation of the economic effects of climate protection (e. g. abatement of GHG emissions) based on economic models, there is a much **smaller number of studies** dealing with the **evaluation** of **adaptation measures** on the basis of these models. **Adaptation** poses **new challenges for economic models**.

Macroeconomic models are applied whenever the effects of a measure or instrument are likely to penetrate the economy non-linearly and interactions, second-round effects and other interdependencies are to be expected. Due to the high degree of complexity of the macroeconomic feedback effects, the use of **computer simulation** models is recommended (Schenker et al. 2014). Macroeconomic models that were already developed for other issues, in particular for the macroeconomic evaluation of **climate protection policy** and **energy policy**, are used for modelling the **impacts** of **climate change** and **climate change adaptation**. Overviews of the model approaches can be found, for example, in West (1996), FEES (1997), Koch, Harnisch & Blok (2003), IEA (2014) and Lutz & Breitschopf (2016).

In these model approaches, macroeconomic **top-down** models are **linked** with the detailed results of sector models or **bottom-up** models. The regional differentiation must weigh the advantage of modelling international feedback effects against the disadvantage of more complex and often outdated data sets. The **national accounts**, which provide the activities of the state, companies, private households and the rest of the world in the account system and their linkage at the national level in a timely manner on an annual basis, form the **basis** of a **macroeconomic model**. In addition, the **interdependencies** of different economic sectors are described in **input-output tables**. Using

national accounts and input-output data, the **sectoral impacts** and **second-round effects** of measures and instruments can be recorded.

In principle, **three** basic types of **macroeconomic models** can be distinguished according to the underlying philosophy and understanding of the interaction of an economy: (1) Computable General Equilibrium models (**CGE**), (2) static Input-Output models (**IO**), and (3) (macro)econometric Input-Output models (**IOE** – Econometric Input-Output models, according to Máñez Costa et al. 2016). In the context of the economic analysis of climate change effects, these **economic models** were **combined** with **climate models** to create Integrated Assessment Models (**IAM**), in which climate models are linked to **CGE** using a loss function, and Disaster Impact Models (**DIM**), in which the economic effects of catastrophic events on the regional economy were assessed and in which regionalization of CGE or IO models took place.

As already pointed out, macroeconomic models can be used for modelling the impacts of climate change and climate change adaptation, in which the macroeconomic top-down models are linked with the detailed results of sector models or bottom-up models. Using national accounts and input-output data, the sectoral impacts and second-round effects of climate change as well as adaptation measures and instruments can be recorded. The following overview of the modelling approaches found in the literature shall the reader help to understand the results of different modelling approaches and put them into perspective.

<u>Integrated Assessment (IAM) models</u>

Integrated Assessment models (**IAM**) were developed to model the **macroeconomic losses caused by climate change** and the **benefits of climate policy** in a consistent model system. The **aim** is to explore the **complex relationships** between these spheres in an integrated way and to estimate **future developments**. Since climate change takes place on long time scales and the CGEs underlying the economic part are abstract from historical time, IAMs can run far into the future. This is associated with **three** major structural **uncertainties** (Weitzman 2009): (1) inaccurate knowledge of the **future GHG emissions**; (2) uncertainty about the **feedback processes** of the CO_2 cycle, and (3) the **relationship between global temperature and GHG emission**s.

The **interface** at which the IAMs link **climate change** with the **monetary** and **physical effects** on humans are **loss functions**. Typically, at least **one aggregated function** is assumed for each **region** (of countries), which establishes a relationship between the **temperature rise** since the beginning of industrialisation or often the reference period from 1960 to 1990 and the **share of GDP lost** due to climate change. The temperature used as input (usually the average global surface temperature) or other characteristics of climate change, such as sea level rise, are themselves determined by a function whose calibration is based on the assumed **climate sensitivity**, i. e. for example the temperature response to a doubling of the atmospheric CO_2 concentration, usually in 2050. Monetary (rarely biophysical) values are shown on the output side of this reduced relationship. Often a function is used such as:

$$D = aT^b$$

where **D** is the **loss value** (e. g. in US dollars or as a percentage of GDP) and **T** is the **temperature** increase compared to a previous period. Exponent **b** indicates the **form** and **steepness** of the function.

Exponents are set and the loss function is typically continuous. Damages in this model environment can be expressed as a negative change in GDP, the capital stock of an economy remains unaffected.

Over the last two decades, numerous IAMs have been developed, such as the **DICE** model (e. g. Nordhaus 2007), or the regionalised version **RICE** (e. g. Nordhaus 2011), **FUND** (e. g. Anthoff & Tol 2014), MERGE (e. g. Manne & Richels 2004), **PAGE** (e. g. Hope 2011) and for Germany the WIAGEM model (e. g. Kemfert 2002). A **frequently used** Integrated Assessment Model is the **FUND** model (Climate Framework for Uncertainty, Negotiation and Distribution), developed by Richard S. J. Tol (Tol 1997). The current version is called FUND 3.9 (Anthoff & Tol 2014; Máñez Costa et al. 2016). FUND is a global model with 16 world regions and a time horizon from 1959 to 2300. Demographic developments, such as migration, are considered in the modelling, as are various effects of climate change on human health. In general, FUND can also be used to analyse non-market effects of climate change. The atmospheric concentrations of several greenhouse gases, the radiative forcing and specifications regarding temperature and sea level rise represent climate change by several indicators. Sectoral loss functions translate the results into monetary units. The economic core is given by a Computable General Equilibrium Model.

Computable General Equilibrium (CGE) models

Computable General Equilibrium (**CGE**) models are based on the **microeconomic** theory of Léon Walras. Representative households and companies optimize their benefit or profit. Behaviour**al parameters** are calibrated with **literature values** for a **base year** in such a way that key variables are well represented this year. In their pure form, the models assume **complete immediate substitution** and **price adjustment** and they do **not** have any **historical time**. The model solution after the policy measure has been set and the new equilibrium reached can be compared with a basic simulation. The new model solution, in which a more expensive good is used less according to the assumed substitution elasticities, describes a new equilibrium at the end of all adaptation processes. **Prices** drive the **results** to a large extent as well as **efficient allocations of resources**. CGE models are more suitable for **long-term** issues and under the assumption of **functioning markets**. **Adaptation costs** are rather **underestimated**.

Nowadays, CGE models are a frequently used tool to evaluate policy measures (Sue Wing 2004). Policies such as the introduction of a tax or price changes act as an exogenous shock to the economy, which then rebalances itself through its own balancing mechanisms. The models are based on the assumptions of the neo-classical economy and – in their simplest form – do not reflect market imperfections, external effects, unemployment, etc. More advanced models take some imperfections into account.

Static Input-Output (IO) models

The **input-output** account consists of **three input-output tables** and the **supply** and **use** table. The input-output tables provide a detailed insight into goods flows and production links both within the national economy and with other countries (United Nations 2018; Miller & Blair 2009). If this accounting system is translated into matrix notation, the result is a system of equations for which the economist of the same name, Wassily Leontief, was awarded the Nobel Prize in 1973. He used product flow data to construct transaction matrices, which enables the analysis of the interrelations of sectors in an economic system (Leontief 1953; Leontief 1956). IO models focus on the

interrelations of production, where a model needs **inputs** from **other** economic sectors to **produce goods**.

In an IO model, a **policy measure** that leads to **higher prices,** increases the **costs** of all consumers who **cannot switch** to other products in the short term. In the case of **extreme weather events** (including natural disasters such as earthquakes, for which various "disaster research" analyses are already available), this approach is **more suitable** for the assessment than the assumption of immediate substitution possibilities (for homogeneous goods) in a CGE model. It is also possible that due to the temporary loss of production, other delivery routes or production sites may be permanently chosen, thus allowing short-term changes to persist. This can be easily modelled in the static IO model by specific changes to individual parameters. However, long-term adaptation processes cannot be represented in a static IO model. **Adaptation costs** are then rather **overestimated**.

Disaster Impact Research is a common field of application for IO analysis. There is a large number of research projects in which analyses and assessments of the effects of catastrophic events, such as floods or hurricanes, are undertaken. In many of these studies, IO models are used to estimate the direct costs of reconstruction and also the indirect costs resulting from the triggered change in demand (e. g. Haimes & Jiang 2001, Bockarjova, Steenge & van der Veen 2004, Cochrane 2004, Okuyama, Hewings & Sonis 2004). By means of these models, in addition to the direct physical damage (to buildings, etc.) reported by insurance companies and indirect demand-side effects caused by shock, such as changes in demand for intermediate, capital and consumer goods, the effects of catastrophic events on the various economic sectors can be analysed (Máñez Costa et al. 2016).

(Macro)econometric input-output (IOEO) models

Dynamic IO models take time into account. In **macro-econometric IO models**, the **behavioural parameters** are econometrically estimated based on **time series data**. Substitution elasticities can also be zero if no significant correlation has been shown in the past. They reflect the **economic development year after year** and can therefore also reflect the **temporal progress** of the effects of policy measures or instruments. As a rule, the models are used for a medium-term period (often until **2030**, partly until **2050**), because the assumption of **behavioural constancy**, which fixed parameters necessarily implicitly entail, is **less and less** valid with **increasing distance in time.** Of course, this is also a general problem of using socio-economic models for long-term simulations.

With this approach, a **dynamic** long-term simulation model can be developed to describe the socio-economic impacts of climate change. A reference scenario reflects the continuation of the economy under a development of the determining exogenous factors, such as oil price development. To analyse the effects of climate change or adaptation these policies have to be translated into changes of economic quantities and model variables. The changes result in deviations of core economic variables such as GDP, employment or changes of production in certain economic sectors. The deviations can be interpreted as the result of the effects analysed. Examples for this approach can be found at, for instance, Lehr, Nieters & Drosdowski (2016) and Lehr et al. (2020, forthcoming) for the analysis of economic effects of adaptation policies in Germany. On a smaller scale, the H2020 funded consortium SoClimPact[4] analyses downscaling effects for climate change adaptation on European

[4] www.soclimpact.org

Islands. The next section provides an overview of risk assessments on even smaller scales, i.e. local or infrastructure system.

Combining socioeconomic modelling and impact chain risk assessment

In sheer numbers, **most** climate change adaptation activities happen on a sub-national **regional** or **local** scale. In order to inform these activities best, risk and impact analyses, mitigation studies, and climate projections need to be conducted at or broken down to the **same geographical scales**. Regarding **climate** projections, the state of the art is the usage of **ensembles** of regional climate projections, consisting of sets of several different projections. Such multi-model ensembles are frequently used in assessments conducted by the IPCC. Hagedorn, Doblas-Reyes & Palmer (2005) investigated the rationale behind the success of multi-model ensembles in seasonal forecasting and explains why a comprehensive multi-model ensemble may often be superior to the best single model.

Below we present work on **impact assessment of climatic and non-climatic hazards** conducted in two recent EU research projects. We take a look at the work on analysis of consequences resulting of impacts of hazards (man-made and natural) on critical infrastructure (including cascading effects) performed in the FP7 project CIPRNet[5]. This work has later been combined with climate change related Impact Chains in the H2020 project RESIN[6].

CIPRNet – multi-model consequence / impact assessment

The FP7 research project CIPRNet – Critical Infrastructures Preparedness and Resilience Research Network - aimed at developing tangible end-user and stakeholder support in the domains of critical infrastructure protection and resilience and disaster risk reduction. This work resulted in **two software systems** realizing new capabilities for stakeholders. The **first** system, CIPcast, produces **short-term risk analyses** for operators of infrastructure and for crisis managers of **civil protection agencies**. The **second** system, CIPRTrainer, is an advanced **training system** for crisis management staff in civil protection. It realizes 'what if' analysis for exploring different course of action in managing a disaster or a crisis in a simulated scenario.

Both new capabilities, CIPcast and CIPRTrainer, employ consequence analysis for estimating the direct and indirect impacts of man-made or natural disasters on critical infrastructure and the downstream consequences. In terms of terminology, two things should be noted.

Firstly, the project decided to use a different term than 'hazard' in their work on consequence analysis. The project found it helpful to be able to distinguish between the things that could possibly happen and the things that are / were happening. The first category has been named 'threat', the second category 'incident' – the term 'hazard' does not allow this distinction.

Secondly, the project found it useful to distinguish between 'damage', 'impact' and 'consequence'. To put it shortly, damages to critical infrastructure elements produce impacts on their services, which inflict consequences for societal life. The 'impacts' cover cascading failures of dependent critical infrastructure at the time scale of the disaster, the 'consequences' cover short- and longer-term and

[5] CIPRNet – Critical Infrastructures Preparedness and Resilience Research Network, https://ciprnet.eu, accessed Mar 1, 2020.

[6] RESIN – Climate Resilient Cities and Infrastructures, http://www.resin-cities.eu/, accessed Mar 1, 2020.

far reaching effects caused by the impacts, such as resulting economic damage, reduction of well-being of people and so on (see figure below).

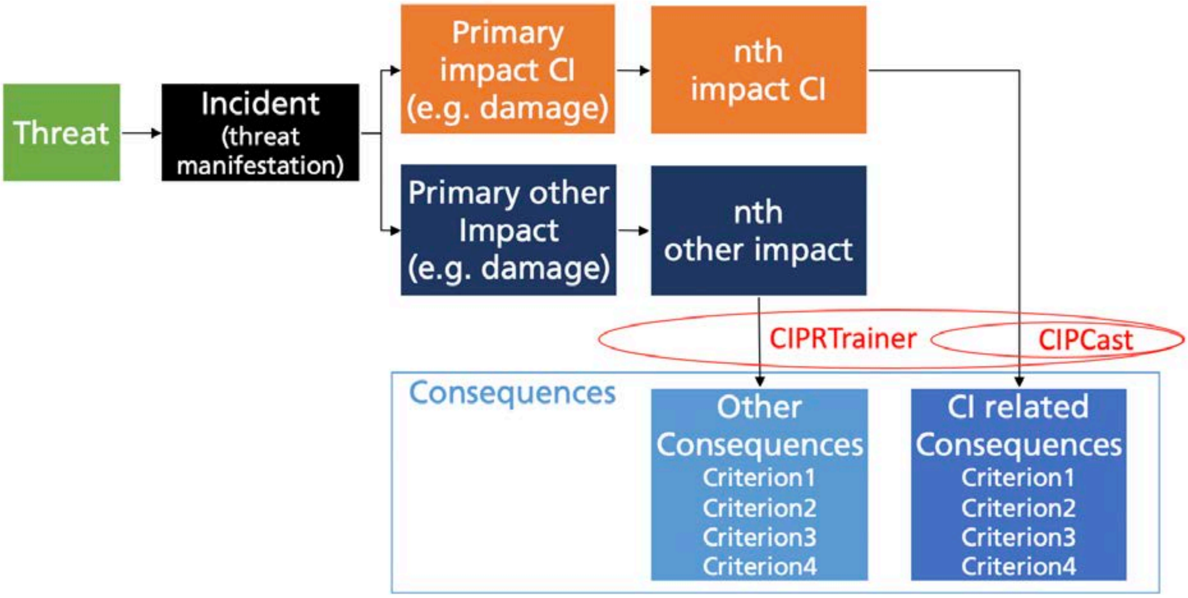


Figure 12 *Scheme of the consequence analysis approaches developed in CIPRNet (Own figure)*

As mentioned above, the aim of developing **CIPRTrainer** (Xie et al. 2016) was to create an additional **training system** for crisis management staff – besides the standard physical and table-top exercises – providing a new capability, 'what-if' analysis. The underlying idea was simple: in a **real crisis**, **decisions** have to be taken under **time pressure** and it is mostly not possible to revert such decisions. In some situations, there is more than one possible course of action (CoA) that could be taken. How to decide which course of action is the better one? In a computer simulation of a crisis as performed by CIPRTrainer, it is indeed possible to revert a decision taken by going back in simulation time and follow an alternative CoA. In order to assess which CoA was the better one, one needs a method for estimating and comparing the final outcomes of the CoAs. This is what the consequence analysis module of CIPRTrainer provides. It employs separate models for damages to humans and economic damage (as an ethical principle, there is no monetarizing of lives or well-being of human beings). CIPRTrainer's consequence analysis module applies these models to the resulting situations at the end of the CoAs chosen in the training session. Since it is usually not possible to avoid all damages, response or mitigation actions are rather aimed at minimizing the damages. CIPRTrainer displays the results in various forms: tabular, color-tagged geographical areas, and column charts. The results include as consequences for humans: number of injured people, number of fatalities; and as economic consequences: Value of Lost Loads households, reconstruction costs for residential buildings, business buildings, and infrastructure, and costs for emergency forces. It should be noted here that emergency forces have their strict priorities: first rescue humans, then rescue animals, and finally mitigate other damages. CIPRTrainer does not recommend any order of response action.

In the next two sections, we first describe how consequences for humans are assessed in CIPRTrainer and then how economic consequences are estimated. In the demonstration scenario used in CIPRTrainer training sessions with stakeholders and end-users, the authors of CIPRTrainer have employed a Dutch-German cross-border disaster scenario. For this reason, the following description of the CIPRTrainer approach to consequence analysis refers to some Dutch and German sources for specific models and computation methods.

Consequence analysis: assessing impacts on humans and their consequences

Impacts on humans can lead to **injuries** and **death**. For operationalization, **mortality functions** can be used. The authors of CIPRTrainer's CA module based their approach on a general framework for loss of life estimation from Jonkman, Lentz & Vrijling (2010). The basic principle is to look at the **exposed individuals** to a certain **hazard**. If people are informed, they can shelter (i.e. keep the door and windows closed when a chemical cloud is coming, going upstairs in case of a flood etc.). If they **cannot shelter** nor **self-evacuate**, they are **exposed** to the threat. Emergency forces can **evacuate** them if present (depends on the training user's decision), **otherwise** they are **exposed** until the **end** of the threat. The effects of the impact on people exposed are calculated with hazard specific mortality functions. The more intense an impact is (e.g. high flood depth and rise speed of water during a flood; time of day, during the night or during rush hour) the more casualties are to be expected.

The **inherent mobility** of humans brings some conceptual issues. Usually, **residential** data is used to assess impacts on humans, i.e. data on areas and buildings in which people live. But this leads to an **overestimation** of impacts on residential areas during daytime, as normally a big part of the residents is at work (or school, university) or pursues other activities (e.g. shopping).

Other researchers have developed approaches for capturing the **varying presence** of people in urban areas, including simple binary distinction between day-time and night-time, such as Freire & Aubrecht (2012) and Leung, Martin & Cockings (2010), and the more complex modelling of the dynamic behaviour of commuting workforce (Polese et al. 2014). Regarding CIPRTrainer scenarios, the data available were not enough for the dynamic modelling of the population. Thus, a simplified approach was used considering only residential data.

Consequence analysis: assessing economic impacts and their consequences

The **impacts** on buildings, **infrastructure** elements and environment are conceptualized in a **similar** way as impacts on **humans**. **First**, these objects need to be **physically exposed** to a hazard, e.g. a house must be in the flooded area. **Second**, the object must be **vulnerable** to the hazard. The damage depends on the **intensity** of the **hazard** (e.g. flood depth) and the **degree** of **sensitivity** of the object to the specific threat (e.g. the main material of the building: wood vs. brick). Some **damage functions** for specific threats and specific objects are available in the literature. For flooding, the authors drew upon the 'Standard Method 2004 Damage and Casualties Caused by Flooding' from the 'Ministerie van Verkeer en Waterstaat' (Kok et al. 2005) of the Netherlands and the book 'Hochwasserschäden' (Thieken 2010) for Germany. But not for all types of objects and hazards are damage functions readily available. In these cases, the authors of CIPRTrainer's CA module have made assumptions based on available damage functions.

To assess the **direct consequences** on a specific building, infrastructure element or environmental area, one needs a metric to express the **value of the damage**. The authors of CIPRTrainer's CA module decided to use **reconstruction cost** for this purpose, because information about the potential reconstruction cost of residential, commercial, industrial and public buildings are derivable from official data on construction cost in Germany and the Netherlands. For infrastructure elements and the environment, a variety of data sources exist. To calculate the actual reconstruction cost for a specific object a damage factor is needed. This is conceptualized as a value between 0 and 1, with 0 no damage and 1 total destruction. This damage factor is determined by the impact module (e.g. flood-depth-functions). The **actual reconstruction cost** of a specific element is defined as a **function** of the **damage factor**.

For the estimation of **power outage cost,** empirical studies are a common method. There are studies which use **historical data** to derive cost estimates. For example, Lawton et al. (2003) published the results of an analysis of studies on power outages costs in the USA in the 1980s and 1990s. Other authors collect new data through empirical studies with power customers, for example LaCommare and Eto (2004). For Germany, there are studies available from the "Hamburgisches WeltWirtschaftsinstitut" (HWWI; Piaszeck, Wenzel & Wolf 2013) and from the "Institute of Energy Economics" at the University of Cologne (Growitsch et al. 2013).

For the CA module, its authors built upon the work of HWWI and conceptualized the consequences of power outages as the estimation of the 'value of lost loads' per hour (VOLL, Piaszeck, Wenzel & Wolf 2013, p. 6-9). For businesses HWWI used an indicator that shows how much output is produced by one kWh for a specific sector:

$$VOLL_{business} = \frac{GrossValueAdded}{ElectricityConsumption}$$

With the knowledge about how much electricity is consumed in an hour and the assumption of zero substitutability of electricity, they estimate the outage cost per hour.

For **households**, it is more difficult to conceptualize. HWWI used **welfare gain** from electricity-dependent leisure activities as approximation. For the quantification of welfare gain for one hour of leisure, they used average net wages per hour as a proxy. The microeconomic optimality condition is that at the margin the benefits of one hour of leisure is equal to the opportunity costs in terms of foregone labor income. As a further assumption, they propose that 50 percent of all leisure activities are electricity dependent.

$$ValueOfLeisure = 0.5 * AverageLeisureHours * NetWagesPerHour$$

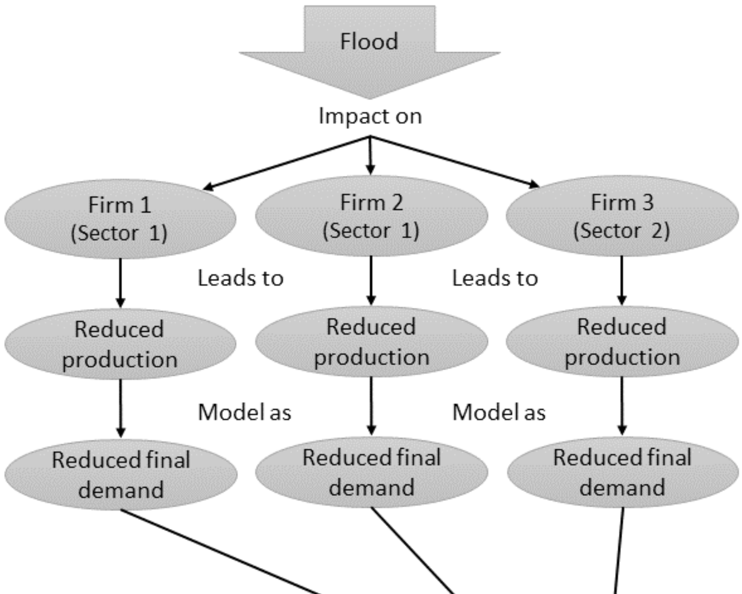
$$VOLL_{households} = \frac{ValueOfLeisure}{ElectricityConsumption}$$

The VOLL values for the different districts in Germany for 2010 are available in the study (Piaszeck, Wenzel & Wolf 2013, p. 17 and 19).

There are basically **two** major streams in economic theory for the consequence analysis of disastrous events: (1) **input-output models** (IO), and (2) calculable **general equilibrium models** (CGE). Both modelling approaches address the interaction of the different economic sectors. They differ however in which manner these sectors interact and how the sectors react to external shocks (Hallegatte 2014, p. 43–44; Okuyama 2007, p. 116–118, Lutz et al. 2018; Máñez Costa et al. 2016). IO-models focus on the interrelations of production, where a sector needs inputs from other sectors to produce goods. In the basic IO-model prices do not play any role.

With the help of the method of IO-modelling (see section above), the effects of business interruption can be estimated. Impacts on buildings and infrastructure can lead to a reduced output of certain economic sectors. This leads to a decrease in the production of final goods and subsequent a reduction in all dependent sectors. The dependencies are operationalized as coefficients. Input-output tables are available for Germany from the German statistical office and for the Netherlands from the Central Bureau for Statistics (CBS). The input coefficients are directly available for Germany, for the Netherlands they have to be calculated from table data (see example for technology matrix below).

The **basic input-output model** bases on the **Leontief production function**, which has several **properties**: Linear production function, one good per sector, fixed input coefficients, and no input substitutions. These assumptions **limit** the **explanatory power** of the basic model, especially for **longer** time periods. However, in the short term directly after a disaster the assumptions can be an acceptable approximation. In the course of time many variations and extensions of the basic model were proposed in the literature (e.g. inoperability IOM (Santos & Haimes 2004, Lian & Haimes 2006), supply-driven IOM (Smith et al. 2010)). For CIPRTrainer the authors decided to start with the basic model as it is the least data hungry and easiest to understand end-users.



Input-output table	**Buying sectors**			
Selling sectors	Sector 1	Sector 2	Final demand	Total utilisation
Intermediate inputs Sector 1	30 → 20.8	220 → 167.2	50 → 20	300 → 208
Sector 2	150 → 104.2	100 → 76	250 → 200	500 → 380
Primary inputs	120 → 83.2	180 → 136.8		
Total production	300 → 208	500 → 380		GDP 800 → 588

Figure 13 *Concept for using IOM. Source: Own figure.*

One obstacle for the use of IOM in CIPRTrainer was the **lack** of **regional input-output data**. There are proposals in the literature how to regionalize national data (see Flegg & Tohmo (2013), Kowalewski (2012), Kowalewski (2013), West & Lenze (1994)), but using one of these methods is a very complex and time-consuming task, hence it was not feasible in the timeframe of the CIPRNet project. The authors decided to take a much simpler approach, even if this led to a less realistic estimation of the economic consequences. The main goal with the CA module was to give the trainee feedback about his or her actions; the authors deemed a less precise estimation of indirect economic consequences acceptable. Their approach was to assume that the regional input-output structure is the same as on the national level. The absolute values for the different sectors are proportional to the GDP share of the region. For the district 'Kreis Kleve' in Germany, the GDP share was 1.3% of the national GDP in the year 2011. The IOM uses this 'regionalized' IO-table data. Another obstacle is the lack of output data on business level, i.e. how much a business is producing in one year. The authors needed to refer to a combination of value-added data on the district level and data on the number of firms with a specific NACE-code in the district to generate a dataset on value-added per firm with a specific NACE-code.

CIPRTrainer Consequence Analysis – some final words

The consequence analysis approach employed for CIPRNet's CIPRTrainer application bears some coarse **resemblance** to **climate change impact assessment**, namely 1) the need to **break down models** to a **local** or **regional** scale (as in the regionalization of climate change projections) and 2) to use a **combination** of several **different models** (as in the ensemble approach). The study conducted by CIPRNet for assessing consequences of a flooding hazard and a derailed cargo train disaster provided some insights into the difficulties of this type of modelling. As far as the assessment of damages to humans are concerned, factors such as the time of day and the dynamics of human movements need to be considered for getting plausible estimates. In the night-time and on holidays there are typically much less people at their workplaces than during daytime of a workday. Seasons also matter. As far as assessing economic damages are concerned, the lack of regional input-output data constituted an obstacle. The authors used a less precise approximation based on the region's share of the national GDP. But even with better data, it has yet to be shown that the precision of the assessment of economic damages can be better than an order of magnitude (meaning powers of ten).

CIPcast – consequence analysis based on SAWI

One of the goals in the development of CIPcast was to maximize the utility of the system for its target audiences, emergency and crisis managers at operators of infrastructure and civil protection agencies. The produced risk assessments should be as comprehensive and useful as technically possible and feasible with the available resources, information, and data. For this reason, the CIPCast developers focused their approach on consequence analysis on critical infrastructure (CI) perturbations and their consequences on societal life, to provide operators and emergency managers a realistic 'score' of the impact of a CI perturbation. For the case study performed in a large European capital city, the CIPCast developers looked at three different but interconnected infrastructures: electricity distribution network, telecommunication network, and the drinking water supply system. The risk analysis considers single units in an infrastructure, their risk of failure, and how this failure propagates within one infrastructure and to the interconnected other infrastructure systems.

The starting point of the consequence analysis is the monitoring of natural phenomena (such as weather nowcast). CIPCast then proceeds with the prediction of natural events (such as short-term forecast of extreme precipitation), the prediction of damage scenarios (such as damages to CI elements in a location that is expected to be hit by extreme rainfall), followed by the prediction of impacts and consequences and recommendations of response and mitigation actions. The damage prediction is based on the analysis of historical maintenance data, which give clues which CI elements are prone to fail in which weather scenarios.

CIPCast's consequence analysis module, called 'block B4 – Prediction of Impact and Consequences' converts the expected damages of CI elements into impact on the services the CI elements produce. This is the core of the prediction process as, in this block, the DSS transforms the expected punctual damages (to one or more CI) into a reduction (or loss) of services. To do that, CIPCast needs to deploy dependence data connecting the different CI in order to reproduce faults propagation. In addition, starting from the inoperability (or partial operability) of the different services, this block also estimates the consequences that the loss of services produces on citizens, public services, industrial activities and the environment. The consequences for each considered societal sector are estimated based on specific metrics; a distinct 'consequence score' on each societal life domain is presented separately (a unified score is not produced) in order to describe the severity of the expected crisis under many viewpoints.

The authors have identified the following four sectors of societal life as most vulnerable to be affected by unavailability (or an only partial availability) of CI services:

- Sector 1: **Citizens**. The consequence metric C1 provides a measure on the number of Citizens affected and the extent of the reduction of the well-being caused by the CI service outage;
- Sector 2: **Economic activities**. The consequence metric C2 estimates the amount of the GDP lost due to CI service unavailability or reduction;
- Sector 3: **Public activities** and **services** such as schools, hospitals, public offices. The consequence metric C3 indicates the number of affected activities and/or their reduction of capabilities (CI service outages or reduction could lead to a reduction in the number of healed patients per hour in a hospital, while partial blackouts could reduce the number of potential users of public transportations etc.);
- Sector 4: **Environment**. The consequence metric C4 provides clues about (long term and short term) environmental damages (dimension of polluted areas, expected costs for reclaiming etc.).

The authors call the availability of services in a societal sector **'Wealth'**. The consequences of unavailability or reduction of service provided by a CI may cause as consequences reduction of Wealth. The Wealth of a societal sector is computed as a weighted sum of the Wealth of all the sector's elements. In order to distinguish elements in a societal sector that are more vulnerable to a loss of CI services, the authors introduce special indices, called Service Access Wealth (SAW) indices. The tables below show the selected sectors, their elements, the approach for identifying SAW indices, and the data used for quantifying the SAW indices.

Table 7 *List of all considered sectors elements for the CA analysis (di Pietro et al. 2017)*

Sector	Elements			
Citizens	Age t > 65	Age 0 < t < 5	Age 18 < t < 64	People with disabilities
Economic activities	Primary sector	Secondary sector	Service sector	
Public services	Schools	Hospital	Public transportation	Safety and security
Environment	Land	Sea	Water basins	

As a preparatory step for computing the Wealth (or reduction thereof) of any of the four societal sectors, a matrix is formed that maps the elements of that sector to the CI that provide service to the societal sector elements. The matrix elements are the SAW indices, determined as indicated in two of the tables below. Once all matrices for the four societal sectors have been determined, the overall Wealth reduction for a damage scenario can be computed. For a more detailed explanation of the approach and the method, see di Pietro et al. (2017).

Table 8 *Association of the relevance concept to each of the CA sectors (di Pietro et al. 2017)*

Sector	Wealth metrics	Concept used to identify SAW indices
Citizens	# Affected people	Level of usage of each CI services in the daily life; prioritization according to safety and discomfort level
Economic activities	Turnout loss	CI services role in allowing the achievement of the production goals
Public services	Service capability	CI services role in making the services available to citizens and stakeholders
Environment	Areas affected	

Table 9 *Type of data used for the identification of SAW indices for a given sector (di Pietro et al. 2017)*

Sector	Wealth metrics	Data used to determine SAW indices
Citizens	# Affected people	Hours of usage and priority of the different CI services
Economic activities	Turnout loss	Yearly expenditures for having available the different CI services
Public services	Service capability	Elicitation with stakeholders and Public Services operators
Environment	Areas affected	Elicitation with stakeholders and Environmental operators

<u>RESIN – Impact and Vulnerability Assessment for Vital Infrastructures and built-up Areas (IVAVIA)</u>

RESIN[7] was an EU-funded research project running from 2015 to 2018. It developed standardized **methods** and **decision support tools** for producing **local adaptation strategies**. It was one of the first large-scale research projects based on the conceptual approaches of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2014b). The **change** in **risk** and **vulnerability concepts** introduced in this report led the researchers to explore the **combination** of approaches

[7] RESIN – Climate Resilient Cities and Infrastructures, http://www.resin-cities.eu/, accessed Mar 1, 2020.

from **climate change adaptation** and **disaster risk management** (Connelly et al. 2018). One of the developed methods is the **risk-based vulnerability assessment methodology** IVAVIA, which **combines** the **indicator-based** method from the original Vulnerability Sourcebook (BMZ 2014) with the **multi-criteria impact and likelihood analysis** by the German Federal Office of Civil Protection and Disaster Assistance (BBK 2011).

The IVAVIA method

IVAVIA consists of a three-stage process of co-creating knowledge for risk-based vulnerability assessment for urban areas based on Impact Chains. The three stages are the qualitative assessment of climate related risk, the optional quantitative assessment, and the presentation of assessment results (Lückerath et al. 2018).

In this review, we want to focus on the **impact assessment part** of RESIN's approach to climate change risk analysis, for which the developers of IVAVIA proposed to adapt the consequence analysis methods of CIPRNet. Depending on the data and resources (in terms of personnel, time, and funds) available, one of **three** approaches to impact-assessment is employed:

- **Damage functions correlate hazard intensity**, often quantified using a single measure, with potential damage. For example, flood depth-damage functions relate flood depths to damages; these may be damages in terms of monetary values, reductions in travel speed, number of fatalities, or other damages. Sources for damage functions include, for example, the JRC Technical Report on global flood depth-damage functions (Huizinga, de Moel & Szewczyk 2017) or the standard method for damage and casualty estimation in the Netherlands (Kok et al. 2005). A damage function that has an associated mathematical model can be calculated by computer programs (such as Mixed Integer Linear Programming (MILP) algorithms).
- **Inter-/extrapolation** is used if historical data on past intensities and impacts is available. In this case historical data is analysed and used to define damage functions by inter- or extrapolating the consequences resulting from historical hazard intensities and probabilities.
- **Expert judgement** is employed if absolutely no other data is available. Here, local experts qualitatively estimate the impacts resulting from the given hazard intensities.

The vulnerability of the exposed area about the specific hazard influences the potential impacts. Therefore, vulnerability scores influence the consequence analysis. How this is achieved depends on the employed method and on the scale of the calculated vulnerability values. For example, building damages from fluvial flooding are estimated by multiplying damage values obtained from generic flood depth-damage functions with **vulnerability value**s – assuming a scale from **0** (**'optimal'**) to **1** (**'critical'**). Thus, regions with the highest vulnerability value suffer the maximum amount of damage under the given hazard intensity, while regions with lower vulnerability values only suffer reduced damages. In this case, the damages estimated using the flood depth-damage functions are interpreted as worst-case consequences, reduced by the vulnerability values to derive expected damages. These expected impacts are then classified in discrete impact classes following the approach of the German Federal Office of Civil Protection and Disaster Assistance (BBK 2011).

Impact Chains will usually contain **multiple impacts** and subsequently, **multiple** expected **consequences** will need to be estimated, e.g. damages to buildings as well as transport infrastructure in Euro. To aggregate different consequences to a **single** impact value, **each impact** and **probability class** is assigned a **numerical** value. **Aggregation** of **multiple** impact **values** can then be done using standard **aggregation methods**, e.g. weighted arithmetic or geometric mean. However, it is important to be **cautious** when combining different impacts. Damages are not only addressing objects that can be restored by providing a enough money. For example, cultural heritage or lives may be lost, which cannot simply be measured in terms of budgets. In this case, the impacts are **not** aggregated, but kept **separate** instead, resulting in **multiple scores**, e.g. for **material** impacts and consequences to **humans**.

In addition to the exposed object directly defined by the Impact Chain (e.g. built-up area), further exposed elements might need to be considered when estimating impacts, depending on the impacts defined by the Impact Chain. For example, if fatalities and injuries should also be assessed, data on the exposed population needs to be gathered, in addition to building data. This also includes **cascading impacts** resulting from a hazardous event, e.g. effects of traffic disruptions caused by flooding or economic losses due to disrupted supply chains. The occurrence of **cascading effects** is an especially **important** characteristic when considering impacts on **critical infrastructures**. Cascading effects in a single critical infrastructure can be modelled as secondary Impact Chains, at a high level of abstraction from the physical level. Damages from cascading effects can be estimated using different methods: Simulation models can be employed to estimate traffic disruptions resulting from flood-related rerouting, while input-output models can be used to model links between economic sectors and subsequently economic impacts.

RESIN – some final words

For getting a **comprehensive assessment** of the impacts of climate change induced hazards, the **downstream** impacts should be included. This is, however, a **challenging** task, since the impact chains may extend **regionally**, **nationally**, **internationally**, and even **globally**. Detailed **quantitative** assessment that **extends beyond the local or regional geographical focus** seems **not feasible** to date for several reasons: lack of data, lack of common reference frame, differing age of data, and so on. But the identification of **critical dependencies**, downstream and upstream, is **possible**. Techniques for doing this have been developed in other domains (Luiijf et al. (2010)), most prominently in the domain of Critical Infrastructure Protection and Resilience (CIP / CIR). Identified critical dependencies may foster collaboration with stakeholders in other regions for planning and implementing joint adaptation measures for reducing mutual impacts. An obvious example is the collaboration of neighbouring stakeholders along rivers for developing and realizing flood protection plans. But it could also be a more sophisticated collaboration, such as including also operators of water reservoirs, operators of hydropower plants and regulators of groundwater of opencast brown coal mines for maintaining water levels of critical rivers during extended drought periods (such as the German river Elbe).

Socio-economic indicators

Task 1.4 provided a general literature review on the use of socio-economic scenario projections in climate research (Lehr et al, 2020). The literature sources identified in this context mainly refer to the so-called Shared Socioeconomic Pathways (SSPs), which were developed by an international research consortium from 2011 onwards in the context of the 5th Assessment Report of the IPCC. and serve to provide internationally harmonised reference assumptions for socio-economic scenario projections.[8]

Quantified estimates of future **developments** for basic socio-economic indicators such as population size, GDP and consumer spending at national and global level are (among other things) already available for the five SSP scenarios documented in O'Neill et al. (2014). These datasets can be freely accessed on servers of the International Institute for Applied Systems Analysis (IIASA).[9] See Riahi et al. (2017) for a more comprehensive documentation of the information content of the IIASA-SSP database.

The current IIASA-SSP database thus provides a necessary framework for quantified scenario projections under alternative, globally harmonised development assumptions. However, for the development and numerical evaluation of individual climate impact adaptation strategies, this information set quickly proves to be insufficient.[10] At least, it appears advisable to supplement the available quantifications by a comprehensive consideration of other socio-economic and biophysical factors in adaptation studies.[11] In the following, potentials for a more detailed depiction of economic interdependencies, especially with regard to a more comprehensive assessment of damage event spill-overs via global supply chains, will therefore be presented.

In this regard, relevant data sets are usually available in the form of so-called Input-Output Tables (IOTs). IOTs record the value of all intermediate deliveries of goods and services between the individual sectors of a national economy as well as the value of final demand in detailed sectoral breakdown. A brief overview of the basic suitability and earlier applications of IOTs for macroeconomic estimation of damage events can be found, for example, in the corresponding section of Hallegatte (2015). For a more detailed presentation of IOTs, derived Social Accounting Matrices, Computable General Equilibrium (CGE) modelling and applications in corresponding impact analyses, we also refer to Okuyama (2007) and Okuyama & Santos (2014).

If statements are to be made about how the direct economic effects of local damage events affect trade links with other regions, so-called Multi Regional Input Output (MRIO) Tables will be required. These are characterised by the fact that detailed demand and supply structures are recorded in a harmonised manner, not only for a single economy, but for various individual economic regions. Generally, individual regions within a national economy (see Oosterhaven & Többen 2017 as an

[8] See Kriegler et al (2012) for a comprehensive presentation of the main objectives of this work.

[9] The current version 2.0 of the SSP Database is available at the following address: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpageage=10#v2.

[10] As the SSPs were primarily developed to simulate climate change mitigation strategies, the SSP Database reflects the (high level of energy technology detail) reporting scope of known Integrated Assessment Models commonly applied in global energy-climate modelling exercise. See, for example, Krey (2014) for a literature review and further methodological comments on corresponding model types.

[11] See, for example, Rothman et al. (2014) or Patt et al. (2010) for a more detailed discussion of this point of criticism.

example) or within multi-national economic areas (see, for example, Koks & Thissen 2016 and Koks et al. 2019) can be mapped by MRIO tables.[12]

For the thematic focus discussed here (international spill-overs of the economic effects of local damage events to other regions of the world), it is particularly important to point out that, at about the same time as the SSP scenarios have been developed, various research consortia produced extensive global MRIO data sets.[13] As these datasets facilitate a complete mapping of global trade linkages of individual economies at the sectoral level, they appear to be particularly useful for estimating the reaction of multinational trade patterns to local damage events. Especially in sustainability research, the usefulness of these data sets for an analysis of multinational supply chains has been comprehensively proven by numerous so-called footprint analyses (see for example Wiedmann & Lenzen 2018 in this regard). However, almost exclusively, ex post assessments have been published so far.[14] And only very few scenario studies have succeeded in deriving the future development of corresponding Footprint indicators from integrated dynamic macroeconomic projections. See Distelkamp & Meyer (2019) and the references to methodologically comparable approaches mentioned there as one of the few successful examples in this regard.

The approach to modelling future economic (trade) structures is obviously of crucial importance for any ex-ante evaluation of international spill-over effects in international trade.[15] From a methodological point of view, all dynamic top-down approaches known from mitigation policy assessments (see, for example, Scrieciu at al. 2013 for a respective methodological overview) could in principle be applied. Until now, however, only very few model-based assessment studies have explicitly focused on tracing the dynamics of multinational trade chains initiated by local damage events. These were mostly based on applications of (CGE) models (Ciscar et al. 2014, OECD 2015, Dellink et al. 2017). Except for Wenz & Levermann (2016) who apply an (agent-based) model for their analysis of the effects of local heat waves.[16]

Overall, it can therefore be stated that, for an analysis of cross-border trade effects of climate change events, the scientific community has access to required data sets (global MRIO databases) as well as established assessment tool (globally regionalised and sectorally disaggregated dynamic simulation models). Nevertheless, such analyses have so far played at best a subordinate role in assessments of the economic impacts of climate change adaptation. The 134-page final report of the JRC PESETA II

[12] Based on preliminary methodological work by Oosterhaven & Bouwmeester (2016), Oosterhaven & Többen (2017) analyse the effects of the heavy rainfall events of 2013 in Germany using MRIO data structures, which divide macroeconomic developments into 16 inner-German regions. Koks & Thissen (2016) and Koks et al. (2019) estimate the further economic impacts of a flood event in the Rotterdam region for more than 250 European economic regions.

[13] Tukker and Dietzenbacher (2013) or Wiedmann and Barrett (2013), among others, offer introductory presentations of these data sets as well as references to first applications of global MRIO data sets in (environmental-economic) policy advice.

[14] See, inter alia, Giljum et al (2015), Galli et al (2017) or Chen et al (2018) as illustrative examples.

[15] It is interesting to note that this challenge is sometimes simply negated. See for example the Water Footprint projections of Zhao et al. (2019) as a reference in this regard. Their analytical approach must be questioned very critically, as it seems qualitatively contradictory to assume a uniform economic structure for (clearly) different climate scenarios.

[16] The applied Acclimate-model is documented in more detail by Otto et al. (2017).

project (Ciscar et al. 2014), for example, devotes only slightly more than one page to a presentation of respective simulation results.[17] Acknowledging that a "national climate change assessment without attention to changes in international trade can lead to misleading conclusions on the effects of climate change on domestic competitiveness" (Dellink et al. 2017, p. 51), we can therefore only recommended that more attention should be paid to this research area in the future.

Conclusions

In short, while the project tries to contribute to the development of a standardized analytical framework for gaining a better understanding of socioeconomic consequences involved in climate change adaptation, it connects different areas of research. To be able to do so, we must understand the current literature on socioeconomic scenarios and pathways and how they include climate change vulnerabilities, exposure and risks. The scenarios developed under the IPCC reports were scrutinized.

Three important factors have been identified to be crucial in the research for UNCHAIN:

1. The element of **scale**. Climate change damages take place on a local or regional scale and do not respect statistical borders, such as federal states, municipalities or countries.
2. The element of **addressing risk and uncertaint**y. Here, the most relevant contribution can be made in the integration of socio-economic model results in Impact Chain assessment as outlined in chapter 2.
3. The relevance of **different economic indicators** for a science-based climate change adaptation strategy. Here, the fact that decision makers as well as the general public often relate much better to socio-economic indicators, such as GDP, production, costs, or welfare makes economic modelling an indispensable ingredient in the mix used for decision supporting information.

As an opportunity, the project can build upon existing work of its members. A good starting point seems to be the combination of dynamic IO models with the case study work on regionalization of economic and societal consequences.

References

Absar, S. M., & Preston, B. L. (2015): Extending the Shared Socioeconomic Pathways for sub-national impacts, adaptation, and vulnerability studies. Global Environmental Change, 33, pp. 83–96.

Alfieri, L., Feyen, L., Dottori, F., & Bianchi, A. (2015): Ensemble flood risk assessment in Europe under high end climate scenarios. Global Environmental Change.

Anthoff, D. & Tol, R. S. J. (2014): The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Technical Description, Version 3.9. URL: http://www.fund-model.org/files/documentation/Fund-3-9-Scientific-Documentation.pdf [13.03.2020].

[17] The European CGE model GEM-E3 Europe is used to simulate the European-wide economic effects of a reduction in agricultural yields in the South and a rise in sea level in the North. The results documented in Ciscar et al. (2014) indicate that the reactions triggered by trade-related reactions across Europe add up to additional losses (in relation to the assumed triggering damage events) in the range of 20%-30%.

Arnell, N. W., Livermore, M. J. L., Kovats, S., Levy, P. E., Nicholls, R., Parry, M. L., & Gaffin, S. R. (2004): Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. Global Environmental Change, 14, pp. 3–20.

Bachner, G., Bednar-Friedl, B., Nabernegg, S., & Steininger, K. W. (2015): Economic evaluation framework and macroeconomic modelling. In Economic Evaluation of Climate Change Impacts (pp. 101-120), Springer.

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., Eom, J., Krey, V., Kriegler, E., Mouratiadou, I., de Boer, H. S., van den Berg, M., Carrara, S., Daioglou, V., Drouet, L., Edmonds, J. E., Gernaat, D., Havlik, P., John-son, N., Klein, D., Kyle, P., Marangoni, G., Masui, T., Pietzcker, R. C., Strubegger, M., Wise, M., Riahi, K. & van Vuuren, D. P. (2017): Shared Socioeconomic Pathways of the Energy Sector – Quantifying the Narratives, Global Environmental Change, Vol. 42 (2017), pp. 316–330.

BBK (2011): German Federal Office of Civil Protection and Disaster Assistance: Method of Risk Analysis for Civil Protection. Wissenschaftsforum, Volume 8, Bonn. ISBN: 978-3-939347-41-5.

Bennett, E., Carpenter, S., Cork, S., Peterson, G., Petschel-Held, G., Ribeiro, T. & Zurek, M. (2005): Scenarios for Ecosystem Services: Rationale and Overview. In: Carpenter, S. R., Pingali, P. L., Bennett, E. M. & Zurek, M. B. (eds): Ecosystems and human well-being: scenarios, vol 2. Island Press, Washington.

Berkhout, F. & van Drunen, M. (2007): Socio-economic scenarios in climate change research: a review. Institute for Environmental Studies, Amsterdam.

Berkhout, F., Hertin, J. & Jordan, A. (2002): Socio-economic futures in climate change impact assessment: Using scenarios as “learning machines”. Global Environmental Change, 12(2), pp. 83–95.

BMVI (2015): KLIWAS – Auswirkungen des Klimawandels auf Wasserstraßen und Schifffahrt in Deutschland. Abschlussbericht des BMVI – Fachliche Schlussfolgerungen aus den Ergebnissen des Forschungsprogramms KLIWAS. BMVI, Berlin, Germany.

BMZ (2014): German Federal Ministry for Economic Cooperation and Development: The Vulnera-bility Sourcebook. Concept and guidelines for standardised vulnerability assessments. Deutsche Gesellschaft für Internationale Zusammenarbeit, Bonn and Eschborn, Germany.

Bockarjova, M., Steenge, A. E. & van der Veen, A. (2004): On direct estimation of initial damage in the case of a major catastrophe: derivation of the “basic equation.” In: Disaster Prevention and Management 13, no. 4, S. 330–336.

Buth, M., Kahlenborn, W., Greiving, S., Fleischhauer, M., Zebisch, M., Schneiderbauer, S. & Schauser, I. (2017): Leitfaden für Klimawirkungs- und Vulnerabilitätsanalysen – Empfehlungen der Interministeriellen Arbeitsgruppe Anpassung an den Klimawandel der Bundesregierung. Umweltbundesamt, Dessau-Roßlau, Germany.

Carey, C. (2014): The CCAFS Regional Scenarios Programme: External Evaluation Report on Progress Towards Programme Outcomes. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark.

Cochrane, H. (2004): Economic loss: myth and measurement. In: Disaster Prevention and Management 13, no. 4: S. 290–296.

Connelly, A., Carter J., Handley J. & Hincks S. (2018): Enhancing the Practical Utility of Risk Assessments in Climate Change Adaptation. Sustainability 2018, 10, 1399; doi:10.3390/su10051399.

Crespo Cuaresma, J. (2017): Income projections for climate change research: A framework based on human capital dynamics, Global Environmental Change, Vol. 42 (2017), pp. 226–236.

Dellink, R., Chateau, J., Lanzi, E. & Magné, B. (2017): Long-term economic growth projections in the Shared Socioeconomic Pathways, Global Environmental Change, Vol. 42 (2017), pp. 200–214.

di Pietro, A., Lavalle, L., La Porta, L., Pollino, M., Tofani, A. & Rosato, V. (2017): Design of DSS for Supporting Preparedness to and Management of Anomalous Situations in Complex Scenarios, Chapter 9 in: Setola R., Rosato V., Kyriakides E., Rome E. (Eds.): Managing the Complexity of Critical Infrastructures A Modelling and Simulation Approach, Springer, DOI 10.1007/978-3-319-51043-9_9

Dreborg, K. H. (1996): Essence of backcasting. Futures 28 (9), 813–828.

Ebi, K. L., Hallegatte, S., Kram, T., Arnell, N. W., Carter, T. R., Edmonds, J., Kriegler, E., Mathur, R., O'Neill, B. C., Riahi, K., Winkler, H., van Vuuren, D. P., & Zwickel, T. (2014): A new scenario framework for climate change research: Background, process, and future directions. Climatic Change, 122(3), pp. 363–372.

FEES (Forum für Energiemodelle und Energiewirtschaftliche Systemanalysen in Deutschland) [Hrsg.] (1997): Energiemodelle zum Klimaschutz in Deutschland. Strukturelle und gesamtwirtschaftliche Auswirkungen aus nationaler Perspektive, Heidelberg.

Flegg, A. T. & Tohmo, T. (2013): Estimating regional input coefficients and multipliers. The use of the FLQ is not a gamble. University of the West of England (Economics Working Papers Series, 1302).

Forrester, J. W. (1973): World Dynamics. Wright-Allen Press, Cambridge.

Frame, B., Lawrence, J., Ausseil, A. G., Reisinger, A. & Daigneault, A. (2018): Adapting global shared socio-economic pathways for national and local scenarios. Climate Risk Management, 21, 39–51. https://doi.org/10.1016/j.crm.2018.05.001.

Freire, S. & Aubrecht, C. (2012): Integrating population dynamics into mapping human exposure to seismic hazard. In: Natural Hazards & Earth Systems Sciences 12 (11), S. 3533–3543.

Gönnert, G. et al. (2017): Second Interim Report, 033W031, supported by the Ministry of Research and Education (BMBF) under the topic Sustainable Water Management (NaWaM). LSBG, Hamburg, Germany.

Growitsch, C., Malischek, R., Nick, S. & Wetzel, H. (2013): The cost of power interruptions in Germany. An assessment in the light of the Energiewende. EWI. Köln (EWI Working Paper, 13/07).

Hagedorn, R., Doblas-Reyes, F. J. & Palmer, T. N. (2005): The rationale behind the success of multimodel ensembles in seasonal forecasting—I. Basic concept. Tellus A 57, 219–233. DOI: 10.1111/j.1600-0870.2005.00103.x.

Haimes, Y.Y. & Jiang, P. (2001): Leontief-Based Model of Risk in Complex Interconnected Infrastructures. In: Journal of Infrastructure Systems 7, no. 1: 1–12.

Hallegatte, S. (2014): Natural disasters and climate change. An economic perspective. Chapter 2: Springer Berlin Heidelberg.

Hope, C. (2011): The Social Cost of CO_2 from the PAGE09 model.

Huizinga, J., de Moel, H. & Szewczyk, W. (2017): Global flood depth-damage functions. Methodology and the database with guidelines. EUR 28552 EN. doi: 10.2760/16510.

IEA (International Energy Agency) (2014): Capturing the Multiple Benefits of Energy Efficiency. Paris

IIASA (2016): SSP Database (Shared Socioeconomic Pathways) – Version 2.0, International Institute for Applied Systems Analysis, Laxenburg. URL: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about [accessed on 27.02.2020].

IPCC (2000): Emissions Scenarios. A Special Report of Working Group III. Cambridge University Press.

IPCC (2014a): Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report to the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

IPCC (2014b): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jacob, D. (2017): Climate Service Center Germany NEWSLETTER 7. GERICS, Hamburg, Germany.

Jiang, L. & O'Neill, B. (2017): Global urbanization projections for the Shared Socioeconomic Pathways, Global Environmental Change, Vol. 42 (2017), pp. 193–199.

Jonkman, S. N., Lentz, A. & Vrijling, J. K. (2010): A general approach for the estimation of loss of life due to natural and technological disasters. In: Reliability Engineering & System Safety 95 (11), S. 1123–1133. DOI: 10.1016/j.ress.2010.06.019.

Kalaugher, E., Bornman, J. F., Clark, A., & Beukes, P. (2013): An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: The case of a New Zealand dairy farming system. In Environmental Modelling and Software (Vol. 39, pp. 176–187).

KC, S. & Lutz, W. (2017): The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100, Global Environmental Change, Vol. 42 (2017), pp. 181–192.

Kemfert, C. (2002): An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem. Integrated Assessment Vol. 3 No. 4, pp. 281–298.

Koch, M., Harnisch, J. & Blok, K. (2003): Systematische Analyse der Eigenschaften von Energiemodellen im Hin-blick auf ihre Eignung für möglichst praktische Politik-Beratung zur Fortentwicklung der Klimaschutzstrategie. Forschungsbericht 299 97311 UBA-FB 000440 im Auftrag des Umweltbundesamtes.

Kok, M., Huizinga, H., Vrouwenvelder, A. & Barendregt, A. (2005): Standard Method 2004 Damage and Casualties Caused by Flooding. DWW-2005-009. Ministerie van Verkeer en Waterstaat.

König, M., Loibl, W., Haas, W. & Kranzl, L. (2015): Shared-Socio-Economic Pathways. In *Springer Climate* (pp. 75–99). Springer.

Kowalewski, J. (2012): Regionalization of national input-output tables. Empirical evidence on the use of the FLQ formula. HWWI (HWWI Research, 126).

Kowalewski, J. (2013): Regionalization of National Input–Output Tables: Empirical Evidence on the Use of the FLQ Formula. In: Regional Studies 49 (2), S. 240–250. DOI: 10.1080/00343404.2013.766318.

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H. & Wilbanks, T. (2012): The need for and use of socioeconomic scenarios for climate change analysis: A new approach based on shared socioeconomic pathways, Global Environmental Change, Vol. 22 (2012), pp. 807–822.

LaCommare, K.H. & Eto, J. H. (2004): Understanding the Cost of Power Interruptions to U.S. Electricity Consumers. Ernest Orlando Lawrence Berkeley National Laboratory.

Lawton, L., Eto, J. H., Katz, A. & Sullivan, M. (2003): Characteristics and trends in a national study of consumer outages costs. 16th Annual Western Conference. Center for Research in Regulated Industries. Online www.crri.rutgers.edu.

Lehr, U., Flaute, M., Ahmann, L., Nieters, A., Wolff, C., Hirschfeld, J., Welling, M., Gall, A., Kersting, J., Mahlbacher, M. & von Möllendorff, C. (2020, forthcoming): Vertiefte ökonomische Analyse einzelner Politikinstrumente und Maßnahmen zur Anpassung an den Klimawandel. Osnabrück, Berlin.

Lehr, U., Nieters, A. & Drosdowski, T. (2016): Extreme Weather Events and the German Economy: The Potential for Climate Change Adaptation. In: Leal Filho, W., Musa, H., Cavan, G., O'Hare, P., Seixas, J. (eds): Climate Change, Adaptation, Resilience and Hazards, pp. 125–141, Springer.

Leimbach, M., Kriegler, E., Roming, N. & Schwanitz, J. (2017): Future growth patterns of world regions – A GDP scenario approach, Global Environmental Change, Vol. 42 (2017), pp. 215–225.

Leontief, W. (1953): Domestic production and foreign trade. The American capital position re-examined. In: Proceedings of the American Philosophical Society 97 (4), S. 332–349.

Leontief, W. (1956): Factor proportions and the structure of American trade. Further theoretical and empirical analysis. In: The Review of Economics and Statistics 38 (4), S. 386–407.

Leung, S., Martin, D. & Cockings, S. (2010): Linking UK public geospatial data to build 24/7 space-time specific population surface models. GIScience 2010: Sixth international conference on Geographic Information Science. Hg. v. University of Zürich. Zurich.

Lian, C. & Haimes, Y. Y. (2006): Managing the risk of terrorism to interdependent infrastructure systems through the dynamic inoperability input–output model. In: Syst. Engin. 9 (3), S. 241–258. DOI: 10.1002/sys.20051.

Lückerath, D., Bogen, M., Rome, E., Sojeva, B., Ullrich, O., Worst, R., Xie, J. (2018): The RESIN Climate Change Adaptation Project and its Simple Modeling Approach for Risk-oriented Vulnerability Assessment (PROJECT NOTE). Simulation Notes Europe, Volume 28(2), selected ASIM/GMMS/STS 2018 Postconf. Publ., p 49-54. DOI 10.11128/sne.28.pn10412

Luiijf, E. A. M., Nieuwenhuijs, A. H., Klaver, M. H., Van Eeten, M. J. & Cruz, E. (2010): Empirical findings on European critical infrastructure dependencies. Int. J. of System of Systems Engineering, 2(1):3–18.

Lutz, C. & Breitschopf, B. (2016): Systematisierung der gesamtwirtschaftlichen Effekte und Verteilungswirkungen der Energiewende. GWS Research Report 2016/1, Osnabrück.

Lutz, C., Becker, L., Ulrich, P. & Distelkamp, M. (2019): Sozioökonomische Szenarien als Grundlage der Vulnerabilitätsanalysen für Deutschland – Teilbericht des Vorhabens „Politikinstrumente zur Klimaanpassung“. Climate Change 25/2019, Dessau-Roßlau.

Lutz, C., Flaute, M., Lehr, U., Kemmler, A., Kirchner, A., auf der Maur, A., Ziegenhagen, I., Wünsch, M., Koziel, S., Piégsa, A. & Straßburg, S. (2018): Gesamtwirtschaftliche Effekte der Energiewende. GWS Research Report 2018/4, Osnabrück, Basel.

Máñez Costa, M.; Rechid, D.; Bieritz, L.; Lutz, C.; Nieters, A.; Stöver, B.; Jahn, M.; Rische, M.-C.; Schulze, S.; Yadegar, E.; Hirschfeld, J.; Schröder, A.; Hirte, G.; Langer, S.; Tscharaktschiew, S. (2016): Synthesis of existing regional and sectoral economic modelling and its possible integration with regional earth system models in the context of climate modelling. Report 27. Climate Service Center, Hamburg.

Manne, A. S. & Richels, R. G. (2004): MERGE: An Integrated Assessment Model for Global Climate Change. http://web.stanford.edu/group/MERGE/GERAD1.pdf [13.03.2020].

Menk, L., Kienberger, S., Terzi, S., Zebisch, M., Rome, E., Lückerath, D. & Meyer, M. (2020): UNCHAIN literature review on the past development and implementation of Climate Change Impact Chains, challenges and knowledge-gaps.

Miller, R. E. & Blair, P. D. (2009): Input-Output Analysis – Foundations and Extensions. 2nd edition. Cambridge University Press.

Nakićenović, N., Alcamo, J., Grubler, A., Riahi, K., Roehrl, R. A., Rogner, H.-H. & Victor, N. (2000): Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Nilsson, A. E., Bay-Larsen, I., Carlsen, H., van Oort, B., Bjørkan, M., Jylhä, K., Klyuchnikova, E., Masloboev, V., & van der Watt, L. M. (2017): Towards extended shared socioeconomic pathways: A combined participatory bottom-up and top-down methodology with results from the Barents region. Global Environmental Change, 45, pp. 124–132.

Nordhaus, W. D. (2007): Accompanying notes and documentation on development of DICE-2007 model: notes on DICE-2007.v8 of September 21, 2007, New Haven.

Nordhaus, W. D. (2011): Estimates of the social cost of carbon: background and results from the RICE-2011 model. NBER Working Paper Series, Working Paper 17540. URL: https://www.nber.org/papers/w17540.pdf [13.03.2020].

O’Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. & Solecki, W. (2017): The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Global Environmental Change, Vol. 42 (2017), pp. 169–180.

O’Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R. & van Vuuren, D. P. (2014): A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Climatic Change, 122(3), pp. 387–400.

Okuyama, Y. (2007): Economic Modeling for Disaster Impact Analysis: Past, Present, and Future. In: Economic Systems Research 19 (2), S. 115–124. DOI: 10.1080/09535310701328435.

Okuyama, Y., Hewings, G. J. D. & Sonis, M. (2004): Measuring Economic Impacts of Disasters: Interregional Input-Output Analysis Using Sequential Interindustry Model. In: Modeling Spatial and Economic Impacts of Disasters, ed by. Yasuhide Okuyama and Stephanie E. Chang, S. 77–101. Springer.

Palazzo, D. (2000): Europe's Environment: The Second Assessment, by the Environment Agency, Office for Official Publications of the European Communities, Elsevier, Oxford, United Kingdom, 1998, 293 pp. Landscape and Urban Planning, 46(4), 254–256. https://doi.org/10.1016/s0169-2046(99)00061-4.

Parson, E., Burkett, V., Clarke, L., Edmonds, J., Fisher-Vanden, K., Jacoby, H., Keith, D., Mearns, L., Pitcher, H., Reilly, J., Richels, R., Rosenzweig, C. & Webster, M. (2006): Scenarios of greenhouse gas emissions and atmospheric concentrations and review of integrated scenario development and application. US CCSP Synthesis and Assessment Product 2.1.

Piaszeck, S., Wenzel, L. & Wolf, A. (2013): Regional diversity in the costs of electricity outages. Results for German counties. HWWI (HWWI Research, 142).

Polese, M., Zuccaro, G., Nardone, S., La Rosa, S., Marcolini, M., Coulet, C., Grisel, M., Daou, M.-P., Pilli-Sihvola, K., Aubrecht, C., Steinnocher, K., Humer, H., Huber, H., Taveter, K., Vassiljev, S., Reda, F., Tuomaala, P., Piira, K., Molarius, R. & Almeida, M. (2014): CRISMA. Version 2 of Dynamic vulnerability functions, Systemic vulnerability, and Social vulnerability. D4.32., CRISMA-Project.

Raskin, P., Gallopin, G., Gutman, P., Hammond, A. & Swart, R. (1998): Bending the curve: toward global sustainability. Stockholm Environment Institute, Stockholm.

Riahi, K., Dentener, F., Gielen, D., Grubler, A., Jewell, J., Klimont, Z., Krey, V., McCollum, D., Pachauri, S., Rao, S., van Ruijven, B., van Vuuren, D. P. & Wilson, C. (2012): Energy pathways for sustainable Development. In: Global Energy Assessment – Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1203–1306.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Crespo Cuaresma, J., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. & Tavoni, M. (2017): The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Global Environmental Change, Vol. 42 (2017), pp. 153–168.

Rozenberg, J., Guivarch, C., Lempert, R., & Hallegatte, S. (2014): Building SSPs for climate policy analysis: A scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation. Climatic Change, 122(3), pp. 509–522.

Santos, J. R. & Haimes, Y. Y. (2004): Modeling the demand reduction input-output (I-O) inoperability due to terrorism of interconnected infrastructures. In: Risk Analysis 24 (6), S. 1437–1451. DOI: 10.1111/j.0272-4332.2004.00540.x.

Schenker, O., Mennel, T., Osberghaus, D., Ekinci, B., Hengesbach, C., Sandkamp, A., Kind, C., Savelsberg, J., Kahlenborn, W., Buth, M., Peters, M. & Steyer, S. (2014): Ökonomie des Klimawandels – Integrierte ökonomische Bewertung der Instrumente zur Anpassung an den Klimawandel. Climate Change 16/2014.

Schweizer, V. J. & O'Neill, B. C. (2014): Systematic construction of global socioeconomic pathways using internally consistent element combinations. Climatic Change, 122(3), pp. 431–445.

Smith, B. J., Vugrinm E. D., Loose, V. W., Warren, D. E. & Vargas, V. N. (2010): An input-output procedure for calculating economy-wide economic impacts in supply chains using homeland security consequence analysis tools. Proposed for presentation at the North American Regional Science Council 57th Annual North American Meetings of the Regional Science held November 10-13, 2010. Sandia National Laboratories.

Steininger, K. W., Bednar-Friedl, B., Formayer, H., & König, M. (2016): Consistent economic cross-sectoral climate change impact scenario analysis: Method and application to Austria. Climate Services, 1, 39–52. https://doi.org/10.1016/j.cliser.2016.02.003

Sue Wing, I. (2004): Computable General Equilibrium Models and Their Use in Economy-Wide Policy Analysis: Everything You Ever Wanted to Know (But Were Afraid to Ask). http://www.rri.wvu.edu/CGECourse/Sue%20Wing.pdf.

Thieken, A. H. (Ed.) (2010): Hochwasserschäden. Erfassung, Abschätzung und Vermeidung. München: Oekom.

Tol, R. S. J. (1997): On the optimal control of carbon dioxide emissions: an application of FUND. Environmental Modeling & Assessment, 2(3), pp. 151–163.

Toth, F. L. (2003): Integrated assessment of climate protection strategies: Guest editorial. In Climatic Change, Vol. 56, Issues 1–2, pp. 1–5. Kluwer Academic Publishers. https://doi.org/10.1023/A:1021316020263

UKCIP (UK Climate Impacts Programme) (2001): Socio-economic scenarios for climate change impact assessment A guide to their use in the UK Climate Impacts Programme. http://www.ukcip.org.uk/ukcip.html

United Nations (2018): Handbook on Supply, Use and Input-Output Tables with Extensions and Applications. Department of Economic and Social Affairs, Statistics Division, New York.

van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., & Winkler, H. (2014): A new scenario framework for Climate Change Research: Scenario matrix architecture. Climatic Change, 122(3), pp. 373–386.

van Vuuren, D. P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakicenovic, N., Kram, T., Berkhout, F., Swart, R., Janetos, A., Rose, S. K., & Arnell, N. (2012): A proposal for a new scenario framework to support research and assessment in different climate research communities. Global Environmental Change, 22(1), pp. 21–35.

Weitzman, M. L. (2009): Some Basic Economics of Extreme Climate Change. URL: https://datascience.iq.harvard.edu/files/heep/files/dp10_weitzman.pdf [13.03.2020].

West, C. T. & Lenze, D. G. (1994): Modeling the Regional Impact of Natural Disaster and Recovery: A General Framework and an Application to Hurricane Andrew. In: International Regional Science Review 17 (2), S. 121–150. DOI: 10.1177/016001769401700201.

West, G. R. (1996): Comparison of Input-Output, IO-Econometric and CGE impact models at the regional level, Economic Systems Research 7, pp. 209–227.

Xie, J., Sojeva, B., Rilling, S., Doll, Th., Voß, N., Rome, E. & Tofani, A. (2016): EU FP7 Project CIPRNet, Deliverable D6.4 “Implementation and integration of the federated and distributed cross-sector and threat simulator”. Fraunhofer, Sankt Augustin, Germany

Transboundary Climate Change Risks

Introduction

The idea that societal change in itself can create risks – even when we are looking at 'external' risks such as climate change – is captured in the notion " risk society" (Beck, 1986) - and have been pursued by a number of authors, in many cases related to studies of catastrophic events like the Chernobyl nuclear accident or major natural hazard events (They & Fabiani 1987 ; Lash, Szerszynski and Wynne 1996 Becerra & Peltier 2009). Below we have selected one of the many theoretical approaches – the works of the American sociologist Charles Parrow - that are available which we think are particularly relevant for understanding and analysing the phenomenon transboundary climate change risks.

In his book "Normal Accidents: Living with High-Risk Technologies" Perrow analysed the complexity of what he calls **high risk enterprises**, such as nuclear power and petrochemical plants (Perrow 1984). Perrow's core message is that the **conventional approach** to make high risk technologies **safe**, i.e. building in warnings and safeguards, is **doomed to fail** for two reasons: Firstly, **failures** are by nature **inevitable**, and even more so in **complex systems** because of their numerous ties to other systems, thus causing incomprehensible or unexpected interactions, and increasing the risk for faults to occur. Secondly, **tight coupling** between system components makes (trivial) incidents more likely to come out of control and develop to (fatal) system accidents. In a follow-up book - "The Next Catastrophe" - Perrow widens the scope from industrial disasters - based on, among other incidents, the 2005 Katrina hurricane - to include also natural perils (Perrow 2007).

Perrow introduces two key-concepts for analysing societal risks at both a company and society-wide level: **complexity** (or interactiveness) and **coupling**.

The former involves the dichotomy **linear** and **complex** interactions. **Linear** systems are characterized by surveyable components sequentially arranged in a way that is fairly easy to follow and comprehend. As systems grow, both in size and number of functions, they become more complex and demanding to operate. Ties to other systems will add to the incomprehensibility, as does operating in hostile environments. In systems characterized by **complex** interactions, **unexpected** outcomes are more likely to occur (Perrow 1984:72). Further, complex systems differ from linear ones in that they have tight spacing of equipment, many common-mode connections, limited options for substitution of supplies and materials, and unfamiliar or unintended feedback loops (page 88).

The concepts **tight** and **loose couplings** stem from engineering and denote the **degree of slack** or **buffer** between items. The term has also been used within social sciences to describe connections within and between organizations (Perrow 1984:90). In both cases **loosely** coupled systems inherit a **flexibility** that, compared to tightly coupled systems, make them more likely to 'incorporate shocks and pressures for change without destabilization' (page 92). This bears many resemblances with the well-known **resilience** concept, i.e. a system's ability to 'bounce back' to the original state after having experienced external stress (Nelson, Adger et al. 2007, Folke, Carpenter et al. 2010). This resilience is partly explained by the **equifinality** of **loosely** coupled systems, which means that the aim of the system can be reached in many ways. This can be seen in manufacturing plants, which are typically organized in ways that make them suitable for a variety of production processes, allowing substitution of raw materials, assembling methods and final outputs, as opposed to **tightly** coupled systems (chemical plants, power grids) characterized by **unifinality**; there is only one way to reach the goal. This lack of flexibility also implies that sequences must follow each other in a specific order, and that processes are time-dependent in the sense that there is no room for delay (Perrow 1984:94).

Perrow suggests that the systems with the **largest catastrophe potential** are those who **combine complexity with tight couplings**. In his later book, where he examines organizational, executive and regulatory sources of failure, Perrow concludes that a society that relies on tight couplings and complex system is inherently more vulnerable also to natural hazards. Although driving for improved efficiency, a "tight" and "complex" society may in fact turn out to become less effective than anticipated in the first place (Perrow 2007).

Despite the complexity and global interdependency that mark our societies and systems, a false assumption appears to underpin much of our approach to adaptation policymaking today, namely that: "the vulnerability of **rich** (and **poor**) countries can be understood **independently** of their connections and **interdependencies** with other countries" (Benzie et al. 2016: 32). This central tenet of adaptation praxis has far-reaching consequences for the assessment of climate risk and the governance of adaptation responses. Dismantling this assumption – to reveal the existence and importance of transboundary climate change risks– opens up the space to **redefine** our entire approach to **understanding climate risk**, with commensurate **implications** for how we **manage** that risk.

Taking Parrow's theoretical strand described above over to the issue of **climate change risks**, we can use the metaphor of tight couplings and complex systems as a framework for analysing to what extent, how and with what climate change related impacts may be mediated from one country to another – creating what has been denoted in literature as 'transboundary climate change risks'. Thus, the idea is that increasingly tight **global** couplings – across nation borders – and complex **global** systems may cause **increasing exposure to transboundary climate change risks** (TCCR). What is then open for discussion is the following:

- the way TCCR are mediated from one country to another
- the nature of TCCR
- the severity of TCCR, e.g. compared with other societal risks
- the methods for assessing TCCR
- ways to address and mitigate TCCR

In this chapter we will assess how the concept of TCCR has been dealt with in the research and policy discourse – considering that the two discourses are closely linked - and thus also investigating to what extent the two discourses have influenced each other.

Method

Two important **clarifications** have been made regarding the methodological approach to the review process in this chapter. **Firstly**, the review **cannot** claim to be exhaustive or systematic. Given the methodological constraints associated with conducting a systematic review of an **emerging** agenda without a commonly agreed and applied terminology (see below), the approach taken was deliberatively **selective** – and both stakeholder-driven (guided by the recommendations of a small number of recognised experts within the field) and iterative (allowing for lines of inquiry to be pursued as the review evolved). **Secondly**, while the review originally aimed to shed light on the extent to which transboundary climate change risks are 'addressed' in relevant policy papers, and the nature of that engagement, the degree to which this topic is still emerging limits the depth that such an analysis could achieve. Analysis to date indicates a high probability that many of the relevant policy documents for the UNCHAIN project – such as the NAPs/NDCs of case study countries, or regional plans such as the EU Adaptation Strategy – may only **superficially** engage with transboundary climate change risks. The next round of NAP submissions and the forthcoming update to the EU Adaptation Strategy, which may adopt more sophisticated analyses, are not yet available. Instead this chapter aims to provide a short overview of the identified **relevance** and **applicability** of evidence on transboundary climate change risks to policymakers, and the insights that a review of the relevant grey literature reveal in this regard.

The findings contained in this review are therefore based on a **selective** and **partial** view of the available literature and could be consolidated and expanded in future. For the purposes of the review, policymakers were defined expansively, to include thought leaders and decision-makers within businesses, civil society organisations, regional or intergovernmental bodies, international institutions and other non-state actors, for whom transboundary climate change risks may be relevant, as well as those in government. The definition of transboundary climate change risk utilised aligns with that noted later in this chapter.

The chapter is divided in two parts with respect to levels of governance: The **international** and **national**, and the **sub-national** (regional and local).

To structure the part of this chapter relating to the **international** and **national** levels of governance, increase its policy relevance and draw out new insights, an analytical framework was applied that has more traditionally been used to reveal the **conditions or determinants of behavioural change**. The 'COM-B' system (Michie et al. 2011) proposes three essential conditions for **behaviour** change that could equally be applied to evidence uptake: **capability**, **opportunity** and **motivation** (see, for example, Langer et al. 2016). While many robust theories of change for policy uptake exist, this framework could reveal opportunities for further research to build upon, and empirical gaps/needs to be addressed, with this stakeholder group and on this emerging agenda.

A total of **13** documents were read and analysed in full. These documents all focus **in detail** on the issue of **transboundary** climate change risks. Many provide a **synopsis of other relevant literature** within the field. A further **five** documents (Defra 2013, Defra 2018, PWC 2013, World Economic Forum 2019, World Economic Forum 2020) were analysed selectively in order to sample **policy-relevant documents** that could reveal examples or case studies relevant to the review, for example to illustrate how a policymaker audience might be interpreting or framing these risks. The **UK** was chosen as a **national-level case study** in this regard – as a noted **'frontrunner'** – and the **World Economic Forum** as a **global-level** stakeholder that provides expert risk and trend analysis at the international level.

Targeted **keyword searches** were used to identify relevant sections of these policy documents, including the following terms: 'indirect', 'international', 'global', 'transnational', 'transboundary', 'cross-border'. In addition, a qualitative search was used to identify relevant chapters and sections for analysis. Two documents were utilised for analytical framing purposes (Michie et al. 2011 and Langer et al. 2016).

As already pointed out, without a commonly and agreed applied terminology, it is challenging to conduct a systematic review on this topic. Being an emerging and narrow topic, the list of relevant publication and document hits are limited. In addition is there an extra dimension to the challenge to look at **sub-national** TCCR adaptation measures due to language barriers. Therefore, we will only have access to documents written in English or Norwegian/Scandinavian. Hence, the review cannot claim to be exhaustive or systematic.

Few systematic evaluations of the sub-national aspects of TCCR exist. One exemption is a limited study conducted as part of the work of the Norwegian government white paper on climate change adaptation (Prytz, Norbø, Higham, & Thornam, 2018). Another study relates to the particular situation of nature management challenges that also involves challenges relating to climate risks crossing borders; namely a regional study on the impacts of Climate Change on the forest massifs located in the Upper Rhine, in the Regional Nature Park of the Vosges du Nord and the Biosphere Palatinate, which concerns France and Germany (Rudolf, Gobert, Averbeck 2019).

Prior to 2010 we have only come across one TCCR study that is exclusively aimed at the local level of governance, for the Norwegian city of Fredrikstad (Sælensminde, Heiberg, & Aall, 2009).

5 documents are investigated in full, focusing on the scoping of TCCR in Norway on a sub-national level. In addition, a few documents were analysed selectively to illustrate how TCCR policy are handled at a sub-national level in Europe. To understand this the national surveys have been investigated to get an overview of national expectations for the local government

Capabilities and motivation for addressing TCCR at the international and national levels of governance

The following sections explore what the review of grey literature revealed regarding the extent to which policymakers have the **capability** and **motivation** to account for transboundary climate change risk. For each thematic area, we have presented a limited number of analytical questions which are then addressed in the text to follow.

Capability

The two analytical question explored here are (Michie et al. 2011, Langer et al. 2016):

- To what extent do **policymakers** (at the national and international levels of governance) have the **theoretical capability** to address transboundary climate change risks
- To what extent could they **access the knowledge, skills and capacity** to identify and manage such risks?

A review of the **grey** literature reveals the extent to which efforts have been made in recent years to better '**define the problem**' and enhance both the knowledge base and the analytical capacity to better assess exposure to transboundary climate change risks.

Various efforts have been made to provide a **definition** of transboundary climate change risks – as "**impacts that are transferred via flows between countries**" as a result of both the effects of **climate change** and our **adaptation/non-adaptation responses** – and to emphasise their potential to have both negative and positive cascading effects (Hedlund et al. 2018: 75; see also Nadin and Roberts 2018). A report by Wei and Chase (2018) goes further to also account for transboundary **'transition'** risks – arising from the **shift to a low-carbon economy** – with the possibility of a 'panicked' policy response in this regard, that increases systemic transboundary risk, also noted by the World Economic Forum (2020).

Efforts to speak a common **language** on transboundary climate change risks have been **hampered** by the sheer **diversity of terms in use** ('transnational', 'transboundary', 'telecoupling', 'teleconnected', 'cross-border', 'cascading', 'indirect', 'systemic', 'international' to name a few) and the **lack of an emerging lexicon** that could be considered dominant (Benzie et al. 2016). But assessments have taken place of each terms' relative merit vis-à-vis respective audiences and proposed definitions of 'transboundary adaptation' have enhanced conceptual clarity of the possible response mechanisms (Benzie et al. 2016, Nadin and Roberts 2018).

A variety of **conceptual frameworks** have been created to group such risks (Benzie et al. 2016, Benzie et al. 2018, Challinor et al. 2017, PWC 2013, Wei and Chase 2018):

- Some have focused on the **inherent nature of the risk,** such as Wei and Chase's classification into (1) acute and chronic **physical** climate risks and (2) policy and legal **transition risks** – following major sustainability reporting standards and the recommendations of the Taskforce on Climate Related Financial Disclosures – and emphasis upon the six capital assets via which to strengthen resilience;
- Others on the **'risk transmission mechanism'**, such as **Benzie et al**.'s four pathways – (1) **trade**, (2) **biophysical**, (3) **people**, (4) **finance**, encased within the global context – or **Challinor's** classification of (1) **material**, (2) **people**, (3) **economic** and (4) **trade** – pointing out that reliance on such flows can either drive increased risk or increased resilience depending on the level of stability of the flow (as affected by climate risk);
- And yet others on **public policy domains**, such as PWC's five themes: (1) **business trade and investment**, (2) **infrastructure and energy**, (3) **food**, (4) **health and wellbeing** and (5) **foreign policy** – based on the "issues that matter to the UK" (PWC 2013: 10) and how likely climate change is to 'multiply' such identified opportunities and threats.

Some recent analytical work has gone further, to classify the different sorts of **events** that can **trigger** transboundary climate change risks (a shock event, a slow onset hazard or an adaptation action), the **means** by which they can be **transmitted** (directly, from cascading effects or via contagion), the different **scales** at which they can spread between and across countries (regionally, teleconnectedly, systemically) – depending on the nature of what Benzie et al. (2014) call the 'receptor system' – and (importantly for policymakers) the different **stages of the risk that responses can be targeted** at (AWBI 2019, Benzie et al. 2018). These different frameworks respectively echo the work of the network actor's school in the French context and the distributed action in the German context (Akrich et al. 2006; Callon et al. 2001; Rammert 2003, etc.). Challinor et al. (2017) also reference the **direction of risk transfer** as a characteristic of note (such as from international to domestic or vice-versa).

Deploying such classifications to varying degrees, various **indicators, metrics and methodologies** have been proposed to subsequently **assess transboundary climate change risk** – including:

- **Quantitative** methodologies such as the **Transnational Climate Impacts Index** – a global index of 192 countries and 9 indicators, measuring exposure to transboundary climate change risk based on a country's level (extent and nature) of global integration and its connections to, or dependencies on, other countries that are vulnerable to climate risk (Benzie 2014, Benzie et al. 2016, Benzie et al. 2018);
- **Qualitative** methodologies such as that posed by Moser and Hart (who propose a typology of eight kinds of 'teleconnections', four of which they go on to qualitatively assess) or PWC's UK

assessment, which maps the projected impacts of climate change and the vulnerability of countries to those impacts (across three timescales, utilising a medium emissions scenario) against the weight/importance of the UK's ties to those countries; PWC are subsequently able to assess the order of magnitude of threats and opportunities that transboundary climate change risks pose to the UK and categorise countries accordingly, accounting for the UK's connections and interests as well as its adaptive capacity to respond (PWC 2013, Benzie et al. 2016);

- **Practical private-sector strategies** for assessing a company's global supply chain for vulnerability to climate change impacts and level of exposure to transition risk (either of which, it was noted, could be transnational in nature or impact) and level of adaptive capacity (Wei and Chase 2018, Averbeck et al. 2019).

Such proposed classifications or methodologies to measure transboundary climate change risk are at an **early conceptual stage**, and often presented as innovations to spur **discussion** and **debate** rather than tools for policymaking purposes (e.g. see Benzie et al. 2016). They have **not yet been adopted** by a great enough number of **stakeholders** (policymakers or otherwise) to create a 'tipping point' or threshold in their results' acceptance, uptake or basis for decision-making.

Nevertheless, the literature notes a number of **case studies** of transboundary climate change **risk**, as well as transboundary adaptation **responses**, that can advance knowledge and understanding of particular risks, albeit in an **illustrative** fashion – from commodity price volatility and subsequent food security on the 'risk' side to shared river basin strategies and private-sector adaptation approaches on the 'response' side (Benzie et al. 2018, Benzie and John 2015, Wei and Chase 2018, Rudolf 2012, 2015 ; Averbeck et al. 2019). Case study analysis has been deployed as a means of 'deep diving' into risks of greatest magnitude exposed by more meta-level quantitative and qualitative analyses (see Benzie and Bessonova 2018 and PWC 2013 for examples), yielding the potential to draw the attention of policymakers with a specific territorial or sectoral remit. It is fair to say there appear many more case studies of the 'biophysical' pathway (of transboundary water resources in particular) than the other three pathways Benzie et al note – reflecting the greater international awareness of such risks and the proliferation of governance mechanisms in response.

The literature also points to a number of examples of **policy-driven assessments and adaptation plans** that either implicitly or overtly demonstrate an awareness of transboundary climate change risk and contribute to deepening the evidence base on the types of risks and levels of exposure countries may face as a result of climate impacts outside their borders (Benzie et al. 2016). These include:

- A number of **national-level climate assessments** that either focus exclusively or in part on the transboundary dimension of climate risk **transboundary** – including Canada, China, Finland, Germany, Kenya, Nauru, the Netherlands, Norway, Sweden, Switzerland, the UK and the USA – as well as National Adaptation Plans (NAPs) and (Intended) Nationally Determined Contributions (NDCs) that reference specific transboundary risks (Benzie and Persson 2019, Benzie et al. 2018, Hedlund et al. 2018, Nadin and Roberts 2018);
    - For instance, the **UK** – an early frontrunner in recognising the importance of transboundary climate change risk – had its first special report on transboundary climate change risks in **2011** (Foresight International Dimensions of Climate Change

2011), drew attention to the transboundary implications of food, water, land, energy, infrastructure, trade and investment in its **2013-2018 NAP**, and to risks associated with global food production, trade, sea management, animal disease, violent conflict and human displacement in its **2018-2023 NAP** (as well as opportunities via expanding international trade routes) (Defra, 2013 and Defra 2018). Following the example of Great Britain and because of its colonial history, France also published early reports that study climate risks from a transnational perspective. The predominant themes are public health, security and defence, agriculture and floods. In the area of public health, a first report in 2005 studies the development of new parasites, of which ticks which are a sensitive subject in the forests of the Upper Rhine (Gauchard and Hattenberger 2005).

- A growing number of **regional** (as in '**supra-national**') climate assessments or adaptation responses such as the European Union Adaptation Strategy – which constitutes "an almost unique experiment of how a supra-national body can define a role for itself in governing the adaptation activities of its member states and of communities within those states including cross-border regions" – and European Green Deal, as well as the South Pacific Regional Environment Programme and the Caribbean Catastrophic Risk Insurance Facility (Benzie and Persson 2019: 372; see also World Economic Forum 2020);
- References and allusions in **international** texts such as the Rio Conventions (discussed at length under 'Opportunities') (Nadin and Roberts 2018);
- **Sector-specific assessments** at a **global** scale, such as exploring transboundary risk within the global trade system (Hedlund et al. 2018).

Importantly, **existing capabilities** to identify and govern transboundary climate change risks were noted to exist **outside the climate sphere**, with Nadin and Roberts (2018) pointing to the wealth of bilateral, regional or multilateral treaties and agreements (on **transboundary water resource**s for example), the relevance of **regional** (supra-national) **commissions** (for instance to govern transboundary river basins, but also regional trade), the growth in **transboundary initiatives and organisations** focused on building supra-national resilience (such as the Africa Adaptation Initiative and the International Centre for Integrated Mountain Development) and the political buy-in to **cross-border movements** (such as the Great Green Wall) – as well as the **risk analysis and management sector** more widely that offers assessments and technical advisory services to governments, private-sector companies and institutions around the world. Transboundary risk is **far from** a 'new concept' and there are **many lessons** to be harnessed in how risks are managed and governed in **other sectors** and domains as well as legislative tools that could be deployed (see below) (Nadin and Roberts 2018). The existence of such expertise, and the identified applicability of relevant legislation, are important in two regards: **First**, in light of their potential to yield **important lessons** that could be transferred to the governance of climate risk more specifically; **secondly**, because they not only set an important **precedent** but could **already** be active in governing aspects of transboundary climate change risk. Both aspects warrant further investigation.

Finally, the literature review revealed a growing understanding of the **systemic nature of risk more widely**, and the role that **climate change** will play in **driving** or **exacerbating** these interconnections and cascading effects. In the World Economic Forum's 2020 Global Risk Report they acknowledge:

> "Countries will face more potential points of contention as climate change reshapes the security of and access to historic common property resources, such as fishing waters. Melting sea ice could enable new shipping routes through the Arctic, as well as opportunities for natural resource extraction, all of which could cause tension between countries already at odds over unresolved maritime and land boundaries… According to the UN, water was a major factor in conflict in 45 countries in 2017; disputes between upstream and downstream areas will likely intensify. And as transition to a more decentralized, renewable energy economy changes geopolitical equations and creates new vulnerabilities for certain states and regions, states' relative position in the international system will shift" (World Economic Forum 2020: 31)

Other examples of transboundary climate change risks and 'disruptions' cited in their 2020 report pivot around changing ecosystems, migration and refugee flows, capital markets, and trade and supply chains – creating "new winners and losers" (World Economic Forum 2020: 33). They explore the impacts of climate change in a country or region being exploited by others for "geostrategic advantage" – posing a risk domestically but an opportunity internationally – and the difficulties of multilateral mechanisms to respond (World Economic Forum 2020: 6).

These factors point to an emerging but nascent capability amongst a small community of researchers to begin to 'assess' the nature and extent of transboundary climate change risks, coupled with a growing 'awareness' and commensurate 'demand' for further assessments of the transboundary nature of climate risk amongst a much wider group of stakeholders (including those with a policymaking remit), as well as potential pockets of expertise to tap outside the climate change community.

However, the literature review also revealed several **empirical hurdles** – arguably constraining the capability of policymakers to identify and subsequently manage such risks. These include:

- The continued **lack** of a clear, commonly agreed and intuitive **lexicon** with which to describe transboundary climate change risks, enhancing difficulties in collating and comparing evidence or assessing relevant responses (Benzie et al. 2018);
- The sheer **complexity of quantifying risk** and level of **uncertainty** and 'unboundedness' associated with the task – which makes it 'resource-intensive' to investigate and challenging to integrate with wider assessments, policies and remits – factors which also lead to a dearth of research and evidence on the topic (Nadin and Roberts 2018 and Benzie and Persson 2019);
- The **empirical challenges** facing adaptation governance more widely – regarding (for example) a **lack** of commonly agreed and comparable **definitions** of **adaptation**, modalities for measuring risk or processes for reporting progress, as well as deficiencies in data access, transfer and management, observational and information-gathering flows, coordination mechanisms (to harmonise priorities and fund cross-border adaptation programmes) and robust risk management responses (Benzie et al. 2018 and Nadin and Roberts 2018); while there is evidence to suggest that existing data-sets and established assessment tools at the pathway or sector level may be applicable (such as the global MRIO databases and disaggregated dynamic simulation models referred to below, or the data-sets used in SEI's Transnational Climate Impacts Index), there are often significant gaps in coverage for relevant indicators, and few models that apply or tailor such assessments to transboundary climate risks specifically, under future climate projections/scenarios;

- The **speed** at which **new knowledge is require**d on transboundary or systemic climate change risks, throwing into question our own adaptive capacity to respond in time (Challinor et al. 2017), and the multitude of **knowledge** or **evidence gaps** that have been identified, including:
    - **Assessments** of the **strengths** and **weakness** of the metrics and methodologies being deployed and iterative development of those with most potential – to incorporate a wider set of indicators, datasets, presentation options and sector-specific contexts or characteristics (PWC 2013, Benzie et al. 2016);
    - Quantitative **methodologies** to accurately **assess vulnerability** (as opposed to exposure) to transboundary climate change risk, accounting for a stakeholder's resilience or adaptive capacity to absorb or manage such risks (Hedlund et al. 2018, PWC 2013);
    - Network analysis and other **methodologies** to **asses exposure** to risks in the second or third degree, the propensity of those of a more speculative or 'cascading' nature – including the existence of 'tipping points' – and the interaction among and between indicators, risks and responses, including how risks and opportunities evolve and can be harnessed or exploited by different stakeholder groups, domestically and internationally (PWC 2013, Benzie et al. 2016, Challinor et al. 2017);
    - **National** or **regional profiles**, **clustering** and **analysis** (Benzie et al. 2016) and **global reports** and **rankings** – such as those presented by the World Economic Forum (2019 and 2020) – including disaggregation by impact, likelihood, theme/domain, timeframe and degree of interconnection – as well as forecasting tools to project future exposure;
    - Greater **evidence** on the ability of transboundary climate change risks to affect **entire multilateral systems** and **appropriate responses** for strengthening systemic and global resilience and weighing trade-offs (PWC 2013, World Economic Forum 2019);
    - Assessments of how to best respond to transboundary climate change risks and the degree to which they **influence** "the range of options – or the costs, benefits and rewards of specific adaptation measures" and potentially support more transformative as opposed to incremental approaches or adaptation plans at greater scales (regional or sectoral for instance) (Davis et al. 2016: 3; see also Benzie and Bessonova 2018);
    - Appraisals of **governance options** – such as the pros and cons of integrating climate adaptation into existing transboundary agreements or building entirely new governance mechanisms, assessments as to the appropriate level of authority that international or intergovernmental institutions should hold to govern cross-border risks, and proposals for the best return on investment between strengthening the mandates and capabilities of those organisations with a climate remit (to account for cross-border risks) or mainstreaming such competences across domains, ministries and sectors (Nadin and Roberts 2018, Benzie and Persson 2019);
- The **imbalance in knowledge** between stakeholders and **erroneous assumptions regarding the extent of knowledge held**: while the private sector are often assumed to be at the vanguard of systemic risk analyses, many companies are yet to assess the direct physical risks

climate change poses to their value chains (let alone the indirect or transboundary risks) and the World Economic Forum (2020: 35) posit that even those who do are "likely to be underestimating them significantly… in the World Economic Forum's survey of business leaders, none of the top 10 risks globally are environmental, suggesting a critical blind spot" – and arguably a need to incentivise the regular transfer/brokering of relevant and accessible knowledge between producers and users and the identification of translators, mediators and conduits in this regard (Averbeck and Frör 2018; Scholze, Glazer and Roy 2018 ; Rudolf 2018);

- A conceptual focus on '**defining the problem**' rather than **'analysing the solutions'** – such as evidence-based studies or political economy analyses on the governance of transboundary risk management, exploring the question of risk ownership (who should own and manage transboundary climate change risks?), what responses are most appropriate for managing or adapting to different kinds of transboundary risks, and what policy options or instruments exist along the pathway from source to impact (for notable exceptions, see those listed in Benzie et al. 2016 and the approach adopted by Benzie and Persson 2019);
- Arguably, a focus on the **production of knowledge** at the **expense of technical advisory services** to enhance skill development and capacity-building to apply such knowledge to the policymaking process. This is understandable, since there is of course a chronological logic to developing methodologies and evidence before investing in the abilities of others to utilise such tools or co-create such knowledge, but there are early signs of a shift in this regard (for example, the first ever NAP Global Support Programme regional training workshop on transboundary climate change risk, for LDCs in Asia, took place in Korea in September 2019).

Motivation

The **analytical questions** posed here are:

- To what extent do national, supra-national or global **policymakers** have the **motivation** to address transboundary climate change risks – either those with an adaptation remit or beyond?
- To what extent are there **incentives** that motivate and drive them to address transboundary climate change risks – individually or collectively?
- To what extent has the concept been **socialised** or **institutionalised** – or **communicated** in such a way so as to encourage policy uptake?
- Are there **constraints** (beyond questions of capability) that might affect the motivation of such policymakers to engage – informational, institutional or structural?
- Are there political or **normative barriers** that prohibit or dissuade analytical engagement and decision-making on transboundary climate change risk (Michie et al. 2011, Langer et al. 2016)?

The literature draws out many 'implications' of a transboundary approach that could theoretically provide incentives or motivations for policymakers to account for such climate risks. These are outlined below.

A transboundary view of climate risk **offers opportunities to develop more comprehensive risk assessments and thus develop more rigorous responses that reduce risk and enhance resilience** – incentivising those tasked with managing and governing such risks whether in public or private bodies. This includes national (and regional) adaptation planners, but also those with wider mandates in ministries/domains that pertain, for instance, to the transboundary pathways via which climate risks can proliferate (such as finance, trade, energy, agriculture, defence, security and foreign affairs), with implications for the policies, plans and regulations (at national or regional level) such actors produce. A transboundary lens acknowledges the systemic nature of climate risk and has the potential to reveal hitherto hidden or underestimated risks ('blind spots'), or the cumulative impact resulting from the interdependencies of those risks, that could serve to significantly increase vulnerability to climate change and which should be accounted for in any effective adaptation plan, or wider national/regional policy as relevant (Beyer 2012; Benzie et al. 2018, Benzie and Bessonova 2018, Challinor et al. 2017).

As the Committee on Climate Change and China Expert Panel on Climate Change 2018 (cited in Benzie and Persson 2019: 373) posit, if an actor is more exposed to indirect transboundary risks than direct domestic risks, or if such risks are of an order of magnitude greater (as PWC (2013) posit for the UK), "a territorial framing, with nationally or locally scaled adaptation, may even be futile or harmful (Banda 2018) and serve to 'inadvertently increase systemic risk'" – a clear case of maladaptation (Benzie et al. 2018). Even where that isn't so, a transboundary lens could undermine long-held assumptions to ultimately strengthen adaptation responses – for example, the geographically dispersed nature of transboundary risks would appear to question the efficacy of a 'copy your neighbour' approach to adaptation that might logically follow an assessment of more 'geographically clustered' direct climate risks (Hedlund et al. 2018). It could also reveal trade-offs to negotiate, when an adaptation strategy to a 'direct' risk increases the level of exposure to an 'indirect' risk and vice versa, as Benzie and John (2015) explore in policy responses to food price shocks.

Wei and Chase (2018) explicitly note the private-sector business case for a transboundary approach to risk identification and resilience-building in international supply chains, as well as the competitive advantages and opportunities such an approach may afford, while Nadin and Roberts (2018) argue that regional adaptation actions that account for transboundary climate change risk could help to 'de-risk' cross-border investments and boost market confidence. Given the early nature of research emerging on this topic, there are arguably gains to be made for frontrunners in identifying such risks and trade-offs and capitalising on the opportunities a more risk-informed approach may yield.

A transboundary view of climate risk also **reveals new winners and losers** – both those who stand to gain should transboundary adaptation opportunities be harnessed and those who could be more vulnerable than an analysis of the direct physical risks implies – incentivising a greater number of national policymakers to engage to protect and promote their strategic interests (Gobert et al. 2017; Benzie et al. 2018 ; Rudolf, Gobert 2019). Whereas 'traditional' assessments imply a high degree of correlation between exposure to direct climate risk, level of development (economic and human) and geography, such factors are less associated with exposure to indirect climate risk – which appears more complex and context-specific (affected by a country's degree of globalisation, and perhaps also by its size, dependencies, location and how landlocked it is) (Hedlund et al. 2018).

The old couplings of 'rich equals resilient' and 'poor equals vulnerable' do not hold true when assessing exposure to transboundary climate change risk (notwithstanding the differential adaptive capacity to respond) (Hedlund et al. 2018). A transboundary lens reveals it is impossible to be "fully insulated" from climate risks transboundary and countries from across the development/income spectrum appear highly exposed (Hedlund et al. 2018: 81; see also Benzie et al. 2018 and Benzie et al. 2016). For instance, the TCI Index developed by Hedlund et al. (2018) suggests that despite ranking low in vulnerability to direct climate risks within their borders, many high-income countries in Europe may be significantly exposed to indirect transboundary risks, a finding also supported by PWC's (2013) UK assessment – turning traditional assumptions about vulnerability on their head. Beck's formula that risk accumulation is inversely proportional to wealth accumulation (Beck 1986) is again tested by the case of complex and transnational risks. The example of the Covid 19 crisis, however, reveals the impact of inequalities in the reception of a crisis. States with high GDP and/or privileged classes generally have resources that can offset the undesirable fallout of risks.

A transboundary perspective also reveals that adaptation activities appearing 'obvious' or 'good for some' could have unforeseen consequences for others – simply redistributing vulnerability or transferring risk as opposed to diminishing it outright – which increases the vested interests of national policymakers in adaptation strategies outside their jurisdictions and relevant supra-national bodies and intergovernmental organisations with relevant remits (Rudolf 2016; Benzie et al. 2018).

A transboundary view of climate risk also **bolsters the case for increased ambition on adaptation, enhanced cooperation on adaptation, and scaled approaches to adaptation**, incentivising regional and global adaptation planners to adopt a transboundary lens. If public or private actors were more aware of the greater number or magnitude of risks climate change poses (as a result of transboundary flows or what has been termed the 'double exposure' of direct and indirect risks) then cost-benefit analysis might tip the scales in favour of more ambitious or transformative adaptation options – while also motivating and incentivising investments in mitigation, including from current climate laggards (Benzie et al. 2018, PWC 2013, Hedlund et al. 2018).

Recognising shared risks within a region could reveal shared benefits in working together that regional policies and agreements could tap or harness (Rudolf 2012 ; Rudolf 2015); recognising exposure to "cascading risks" (Hedlund et al. 2018: 81) or "climate contagion" (Benzie et al. 2018: 4) via a global system could incentivise multilateral cooperation and investments in strengthening systemic resilience that bring benefits to all (Benzie et al. 2018: and Hedlund et al. 2018). With such a view, acting in the collective interest can be assumed *a priori* to be acting in the national interest. In such a world, the benefits of regional or even global adaptation plans and governance arrangements might be realised: both to reduce the risks (as national policymakers acknowledge intersecting transboundary risks are "too large for any one country to address alone" (Nadin and Roberts 2018: 2) and as National Adaptation Plans themselves are found to have 'ripple out' effects) and to reap the rewards (as national adaptation planners recognise their plans are more effective when coordinated and harmonised, that national adaptations may have regional or global benefits that could be harnessed as political capital, and conversely that cross-border cooperation could yield benefits within their borders – such as additional capacity, access to knowledge and expertise, and co-funding opportunities) (Nadin and Roberts 2018; see also Benzie et al. 2018, Benzie and Bessonova 2018, Benzie 2014).

As Davis et al. (2016: 4) argue: when viewed through a transboundary lens, "international adaptation finance is an investment in global economic stability": humanity's collective resilience is only as strong as its weakest member and can only be achieved by "ensuring that all countries have the resources and capacity to adapt". Such arguments should incentivise greater ambition and investment on adaptation from all countries, allowing adaptation to finally be reframed as the "global public good" it always had the potential to be (Khan 2013). An analysis of transboundary climate change risks could also disclose new allies and allegiances to be forged – or those which a country can ill afford to lose – of particular note to any country's foreign policy objectives, while adaptation at scale and across scales could reveal new 'benefits' and 'beneficiaries' to harness transboundary (Benzie and Persson 2019: 373; see also Benzie and Bessonova 2018).

All these factors point to a compelling argument for the value and utility of a transboundary perspective. However, a review of the literature reveals little in the way of tailored arguments, targeted to specific policymaker groups, that would make such arguments more individually compelling (with Benzie's (2014) practical guide for policymakers drafting National Adaptation Plans a notable exception), and also points to a number of **norms, mandates and agendas that mitigate against policy uptake** and the 'socialisation' and institutionalisation of the concept more widely. Despite the conceptual validity of the arguments, several factors pose political and jurisdictional barriers to the adoption of a transboundary lens.

Perhaps most fundamental is **the importance of 'place'** and the emphasis it retains in our governance models and systems: the coincidence between what Benzie et al. (2016) call the 'location-specific nature' of direct climate risks and the location-specific mandate or jurisdiction of most adaptation planners (Benzie 2014). Transboundary climate change risks initiate, by their very nature, outside a country's borders and therefore outside most national policymakers' gaze or purview. Though real and tangible, they can propagate through virtual and abstract systems that are equally hard to grasp and understand. The 'chains' of influence may be convoluted and filled with uncertainty. And tackling them successfully might reduce the risk without the benefit of an obvious reward that elected officials can champion and subsequently stake their claim to.

As Benzie and Persson (2019: 369) discuss at length, the community to which policymakers turned for advice and guidance on effective adaptation approaches – including the IPCC – possessed a number of characteristics (stemming from the disciplines from which they tended to emanate and the research methods they favoured) that "established and subsequently reinforced the territorial framing… reinforced by an international norm that adaptation was primarily a national or local responsibility". The UNFCCC – a Convention which countries (as Parties) ratify – and the architecture of the Paris Agreement, with its emphases on *National* Adaptation Plans, *Nationally* Determined Contributions and *National* Communications, also promote a state-centred lens and the national sovereignty of adaptation plans and actions (Benzie et al. 2018, Benzie and Persson 2019). This has a trickle-down effect: the metrics used to inform adaptation plans are more often than not local or national climate projections rather than vulnerability assessments of the countries upon which a country's stability (economically, socially, politically) may depend (Hedlund et al. 2018). Benzie and Persson (2019) propose three responses to overcome this territorial framing and mainstream/institutionalise a transboundary perspective at the international level – reform of current 'instruments and provisions' (discussed below), the institutionalisation of 'collective risk monitoring' and **new or emboldened mandates** to act on transboundary risk.

The governance of transboundary climate change risk is beset by "fundamental political barriers, such as questions of sovereignty, jurisdiction and responsibility" (Nadin and Roberts 2018: 8). While many national policies beyond adaptation planning are firmly rooted in assessments of regional/global risks and trends – policies which may themselves (explicitly or otherwise) actually account for specific transboundary climate change risks – the cross-jurisdictional nature of the 'flow' of transboundary risks and the diversity of ways in which such risks may manifest (across multiple sectors/ministries) make it **hard to identify who exactly should be held to account** – both across and within national contexts. Transboundary risks emanate, by their very nature, outside a country's **jurisdiction** and the policy responses to manage even specific transboundary climate change risks could **fall beyond the scope of any single department/policy** to address (given their systemic nature). This challenge is reflected in many National Adaptation Plans which recognise transboundary risks but **rarely attribute ownership** or **accountability** for designing an adequate response (Benzie et al. 2016).

Furthermore, what constitutes an effective transboundary response – transboundary "approaches for managing climate risk inter-, trans-, or supra-nationally, at bilateral, regional or even global scales" – and the benefits such a response could bring **have yet to be articulated** (beyond, perhaps, the field of **water governance**) (Benzie and Persson 2019: 370). Nadin and Roberts (2018: 5) articulate some of the **actions** that will be required to facilitate and incentivise such **cross-border responses** – demanding **political will**, **regulatory frameworks** and **financial incentives** – but also question: "where does the responsibility for undertaking transboundary adaptation lie?" Identifying **appropriate mandates** and **common interests** will be **crucial**. As will the emergence of **political champions** or 'ambassadors' of this agenda that can mobilise others (Benzie et al. 2018).

Catalysing adaptation to transboundary climate change risks is beset by the same disincentives that adaptation faces more widely – **low political** will and **low collective ambition**, a crowded political agenda and a multitude of competing priorities within the climate negotiations (Rudolf 2016; Nadin and Roberts 2018, Benzie et al. 2018).

Finally, there is the **overarching political and institutional context** which also affect policymakers' motivations and incentives to recognise and account for transboundary risk. The national and regional political context will influence a policymaker's motivation to address transboundary climate change risk or the space in which they're able to operate and manoeuvre to a great degree, as will prevailing attitudes to risk management and risk tolerance. As Benzie and Persson (2019: 384) note, the lack of adequate and integrated functions to manage long-term or systemic risks is a particularly pertinent 'systemic barrier' at the national level that mitigates against policy uptake of transboundary risk: "many governments work to short policy cycles, and powerful ministries are therefore more concentrated on short-term risks". Even if a government is incentivised to adopt a risk management strategy to address transboundary climate change risk, unless it is widely integrated and mainstreamed, it is perhaps unlikely to outlast its creators (Benzie and Persson 2019).

The **global context** also plays a role. On the one hand, globalisation continues apace – weaving intricate links, building connections and deepening interdependencies between us all – increasing the systemic nature and shared responsibility of the challenges we face; on the other hand, a backlash against the value of multilateral, multi-stakeholder approaches and a surge in competitive, nationalist and protectionist stances can be detected (Benzie and Bessonova 2018, World Economic Forum 2019). Arguably, recognising and responding to transboundary climate change risks require a truly global perspective, cooperation between governments and policy coherence across jurisdictions, and a response that acknowledges the value of collective endeavours, systemic resilience, and trust and reciprocity – indicative of what the World Economic Forum (2019: 5) calls "this generation's defining task' but going against the grain of many popular narratives and political movements today (Challinor et al. 2017).

The **wider context** within which policy uptake of transboundary climate change risks take place (as noted above) also has consequences for the study of such risks that are worthy of note. There are clear implications of an assessment of transboundary climate change risk for a country's foreign policy objectives and approaches. Despite the apparent objectivity of a quantitative methodology assessing risk, subjective bias is always liable to play a role in the indicators chosen and the results that are emphasised – there is no such thing as a value-free assessment. The researcher is also unable to control the policy response to such risks which, far from engendering a more cooperative approach driven by a concern for the 'common good', may be marked by a politician's responsibility to promote the interests of the electorate that they govern and even by populist or nationalist agendas. There is a very real possibility, especially in today's political climate, that an advanced economy's exposure to transboundary climate change risks is used to justify a reallocation of finance towards 'adaptations' that protect or distance that economy's exposure transboundary to the expense or detriment of others (for example toward domestic responses instead of investments at the 'source' of the risk where adaptive capacity is weakest). The repercussions of such strategic or narrowly defined adaptation to transboundary climate change risk could be **very negative for people and ecosystems in the poorest and most vulnerable parts of the world.** Benzie and Persson (2019: 380) refer to this directly:

> "There is a danger that a borderless framing of climate risk stimulates countries to adopt an approach to cooperation on adaptation that is based solely on narrow self-interest, for example by prioritizing the allocation of bilateral adaptation finance in ways that minimize the donor's own exposure to borderless climate risks... It may, for example, lead to the diversion of limited adaptation funds to countries with strategic links to donor countries (e.g. middle income countries that are key high value exporters), rather than the most vulnerable countries, who may be relatively less connected to donors (e.g. at lower tiers of supply chains)."

The risk is also revealed in a number of other texts: from concrete examples, such as the UK's 2018-2023 National Adaptation Programme (Defra 2018), which raises the spectre of quickly switching suppliers (i.e. divestment) as an adaptation approach without reference to the impacts this may have on producers' livelihoods, to the vivid illustrations presented in the World Economic Forum's 2019 and 2020 Global Risk Reports that are worth citing in full:

> "Global risks are intensifying but the collective will to tackle them appears to be lacking. Instead divisions are hardening... The idea of 'taking back control' — whether domestically from political rivals or externally from multilateral or supranational organizations— resonates across many countries and many issues. The energy now expended on consolidating or recovering national control risks weakening collective responses to emerging global challenges. We are drifting deeper into global problems from which we will struggle to extricate ourselves" (World Economic Forum 2019: 6)

And furthermore:

> "The growing palpability of shared economic, environmental and societal risks signals that the horizon has shortened for preventing — or even mitigating — some of the direst consequences of global risks. It is sobering that in the face of this development, when the challenges before us demand immediate collective action, fractures within the global community appear to only be widening… states are increasingly viewing opportunities and challenges through unilateral lenses. What were once givens regarding alliance structures and multilateral systems no longer hold as states question the value of long-standing frameworks, adopt more nationalist postures in pursuit of individual agendas and weigh the potential geopolitical consequences of economic decoupling. Beyond the risk of conflict, if stakeholders concentrate on immediate geostrategic advantage and fail to reimagine or adapt mechanisms for coordination during this unsettled period, opportunities for action on key priorities may slip away… the turbulence threatens to undermine the international community's ability to

> mitigate critical global risks by multiplying the domains in which rivalries can play out and limiting stakeholders' capacity to address global challenges" (World Economic Forum 2020: 4; 6; 11)

There is also a charge that an exploration of transboundary risk could undermine already limited adaptation ambition by crowding out other 'more pressing' agendas or encouraging a fatalist 'it's too complicated' response.

Migration

The specific issue linked to environmental and / or climate migration is a good example that can illustrate the concept of impact chains and point to a necessary transnational adaptation and cooperation. Natural disasters, environmental degradation and other climatic changes (desertification, drought, sea level rise, etc.) cause the appearance of a new form of migration, it is an imposed or chosen migration. According to the article by C. Cournil (2010), nearly 250 million people will be displaced in the middle of this century due to a degraded environment. It is difficult to determine the extent of migratory movements directly linked to the environment or to climate change. There are several names used to talk about this form of migration: environmental refugees, climate refugees, environmental migrants, climate evacuee, eco-refugees, people displaced by natural disasters, environmentally displaced persons, etc. In 1985, Essam el-Hinnawi for the first time defined ecological refugees as "those who have been forced to leave their traditional dwellings, temporarily or permanently because of a clear environmental disturbance (natural or caused by humans) who endangered their existence and or seriously affected their quality of life". This definition is adopted by the United Nations Environment Program but does not provide all the particularities of the category of environmental displaced people. No scientific consensus has been established to date to define the category of environmental migrants.

According to F. Gémenne (2008), there are two approaches to environmental migration. The first considers the environment as a contextual variable that can contribute to migration. Indeed, economic, political and social factors have an important role to play in environmental migration. Isolating environmental factors to define a category of migrants for whom only the environment has influenced the decision to leave seems to be a limited approach. So, it is important to remember that populations do not move only for environmental and climatic reasons, but that different factors (economic, political, environmental, etc.) overlap one another. Only extreme cases can confirm the predominance of one of the factors of migration. As for the second approach, it makes degradations and environmental changes the main reasons for migration. François Gémenne (2008) names the first perspective as a minimalist approach and the second as a maximalist approach that can have an alarmist effect on our contemporary societies. The initial decision to move, in general, is not only related to environmental factors, but can include several reasons of a different order, such as calamities, wars, technological accidents, etc. Hervé Domenach (1995) integrate so-called "post-modern" causes, such as noise, pollution, the search for quality of life, in the reasons for environmental migration. Several variables must be considered in the analysis of environmental displacements. The decision to leave can be made thoughtfully, depending on the urgency. There are two types of displacement, temporary displacement and permanent displacement. Temporary displacement is often attributed to environmental displaced people who are victims of spontaneous natural disasters. The territory of origin and the place of destination are decisive in the process. Several factors must be taken into account, such as the nature of the risk or disaster, the possibility of returning or not to the place of origin, territorial, national or international protection norms, etc. In addition, the displacement of populations generates social, economic and environmental upheavals, which can cause serious ecological imbalances. Temporary or permanent departures thus compromise the functioning of societies, thus affecting the modes of use of space and the management of resources (Domenach and Gonin, 2002).

Environmental migration, as described above, can be included in a chain of impacts. Indeed, it is the influence of environmental factors as determinants of migration, and conversely the consequences of population movements on the environment both for the departure areas and for the arrival areas. Thus, the consequences of climate change will largely depend on societies. They will be responsible for preventing risks and repairing the damage caused. The share of uncertainty and that of predictability must be considered in the migration process. Ignorance of certain aspects of an environmental phenomenon confirms the inability to manage certain situations. However, knowledge can also lead to adopting a preventive approach to environmental risks, whatever the measures adopted. Migration can thus be considered either as a social consequence to be managed, or as a logic of adaptation to be developed. In addition, like the control of capital flows and consumer markets that underpin the dynamics of economic growth, countries must solve environmental problems and manage migration flows by working together. In fact, migration influences economic imbalances, poverty, access to education and health services, use of agricultural land, social reproduction, etc. It is understandable that the question of migration policies and the spatial distribution of populations ultimately concerns more than one government.

Opportunities for addressing TCCR at the international and national levels of governance

The **analytical question** posed here is:

- To what extent can policymakers **account for** or **address** transboundary climate change risk?

For the purposes of this review, this is interpreted as the concrete or foreseeable windows of opportunity that make policy uptake or evidence-informed decision-making on transboundary climate change risks possible or more likely (Michie et al. 2011, Langer et al. 2016). The literature review reveals opportunities at multiple levels and sectors, each of which will be discussed in turn.

<u>International opportunities: climate change governance mechanisms</u>

Opportunities here pivot around the United Nations Framework on Climate Change (**UNFCCC**) and Intergovernmental Panel on Climate Change (**IPCC**) **instruments**, **mechanisms** and **provisions**. Several articles in the Paris Agreement and Convention could be harnessed to justify a focus on transboundary risk in negotiations within the Ad-hoc Working Group on the Paris Agreement (APA) and the Conference of the Parties (COP): article 7.2 of the Paris Agreement which outlines the global nature of the adaptation challenge and its 'international dimensions', and article 4.1F of the Convention which encourages the use of 'appropriate methods' to minimize the 'adverse effect… of projects or measures undertaken… to mitigate or adapt to climate change' (Benzie et al. 2018). A variety of more specific means are also cited in the literature through which transboundary climate change risks could rise up the agenda and/or be mitigated and managed:

- **Instruments** and **provisions**: the Global Goal on Adaptation (to drive collective global ambition and scale up action on adaptation); the Enhanced Transparency Framework and the Global Stocktake (to reveal, assess and compare transboundary risks/effects); National Adaptation Plan guidelines and trainings (to advise countries on how to account for transboundary risk, building on the current advice to work across levels and ensure "synergy and coherence of actions" (5th Meeting of the UNFCCC Adaptation Committee, cited in Benzie 2014: 1); Adaptation Communication and National Communication guidelines (to disclose and communicate transboundary risks either generated or experienced); the Cancun Adaptation Framework, the Nairobi Work Programme and the Marrakech Partnership (to drive concrete advances on the management of transboundary climate change risk, strengthen alignment and collaboration, and reveal links to other agendas); and the TEP-A (to advance technical understanding of the risks and possible responses) (Benzie et al. 2018, Davis et. al 2016, Benzie 2014, Benzie and Persson 2019, Nadin and Roberts 2018);
- **Channels** and **groups**: the IPCC, particularly Working Group II (who could strengthen the evidence-base, with the Sixth Assessment Report noted in particular); the Adaptation Committee and their NAP Taskforce (who could play a pivotal role to assess the risks, provide warnings, build and share an evidence-base, facilitate coordination and enhance cooperation); the LDC Expert Group and NAP Global Support Programme (who could support the co-development of solutions); the Paris Committee on Capacity-Building and the Global Adaptation Network (who could build capacity and share best practice on assessing exposure to transboundary risk) (Benzie et al. 2018, Nadin and Roberts 2018, Benzie 2014, Benzie et al. 2016, Benzie and Persson 2019, Davis et al. 2016);
- **Funding mechanisms**: the Adaptation Fund; the Global Environment Facility; the Land Degradation Neutrality Fund – who could finance cross-border adaptation projects and incentivise the inclusion of transboundary climate change risk in project designs (Benzie et al. 2018, Nadin and Roberts 2018).

The literature review also reveals an opportunity to focus future editions of well-known and anticipated reports – such as UNDP's Adaptation Gap report – on transboundary risks, to build the evidence base but also provide a wake-up call regarding the extent of action required or degree of urgency (Benzie 2014), while the World Economic Forum's (2020) account of the OECD's common principles, adopted to promote 'innovative' yet 'trustworthy' and 'respectful' developments in artificial intelligence, sparks ideas around whether such an approach could be applied in other contexts – a global charter promoting a just approach to managing risk and promoting adaptation, for example.

<u>International opportunities: wider governance mechanisms and legal instruments</u>

Nadin and Roberts (2018: 4) draw our attention to a wealth of opportunities involving **non-climate** conventions, initiatives or processes, including UNCCD (the UN Convention to Combat Desertification), the CBD (the Convention on Biological Diversity) and the Water Convention, as well as a plethora of legal and regulatory instruments ("multilateral, regional and bilateral treaties, international customary law, and soft law instruments, such as memoranda of understanding"), that could **play a role** in managing transboundary climate change risk and guiding transboundary adaptation efforts. The implementation of other international frameworks (such as Agenda 2030) might also provide opportunities to spur action on transboundary risk management, even if they are not legally binding. The latest UN Global Assessment Report on Disaster Risk Reduction (GAR) is notable for its emphasis on systemic risk: it dedicates a whole chapter to exploring ”the systemic risks that are embedded in the complex networks of an increasingly interconnected world” and provides many explicit examples of transboundary climate change risks, including the possibility of 'multiple breadbasket failure' (UNDRR 2019). The report – reviewed fleetingly – merits further analysis and attention.

The diversity of actors engaged in such pursuits points to the utility and value of a multidisciplinary community of practice, proposed by Benzie et al. (2018) and others, which could also support policy coherence across implementation of the international conventions (Nadin and Roberts 2018). Nadin and Roberts (2018) also point to relevant legal concepts that could be deployed – the framing of 'common concern' to describe matters that are of international importance and consequence, and the 'precautionary principle' which outlines – given a high level of uncertainty - a responsibility to notify, consult and cooperate with relevant parties when activities may have adverse effects beyond their jurisdictions in order to prevent harm – as well the diversity of regional bodies, intergovernmental organisations, institutions and commissions who hold expertise in negotiating and managing transboundary issues and who could shed light on identifying and leveraging governance opportunities.

International opportunities: finance institutions and donors

As Benzie and Persson (2019: 379) note "international adaptation finance institutions engage not only in **funding** adaptation but in **governing** how adaptation is practiced, through the rules pertaining to eligible and desirable adaptation activities". They are thus identified as an important target audience in the literature, that perpetuate a 'place-based' framing of climate risk by imposing conditionality (around attribution and results-driven agendas) that naturally channels funding towards mitigating physical climate risks in local or national contexts (Benzie and Persson 2019). Some of the opportunities noted thus centre on the enabling role that both bilateral and multilateral donors can play in:

- Designing programmes and providing adequate financial mechanisms and funding pools to identify and address transboundary risks (including systemic risks), enabling the recipients of aid to bolster their resilience, and reforming rigid rules (such as those imposed by the WTO) that undermine their efforts in that regard;
- Incentivising multi-country adaptation planning, transboundary adaptation programmes and the generation of 'co-benefits' with adaptation at local or national scales;
- Seeding blended finance mechanisms to attract private sector investment (Nadin and Roberts 2018, Davis et al. 2016, Benzie et al. 2018).

National and regional opportunities: governments

The literature review also reveals several opportunities for governments at **all levels** – national to local (see below) – to adopt a transboundary approach to climate risk management. Many studies cite the importance of national assessments – to identify exposure or vulnerability to particular transboundary risks and appropriate governance responses – with National Adaptation Plans and/or

National Adaptation Programmes of Action a concrete opportunity in that regard (Benzie and Persson 2019, Benzie et al. 2018). Such plans could, as Benzie (2014) proposes, dedicate a section on transboundary risks (both risks and responses generated within a country's borders that may impact others, and those the country itself is exposed to that originated elsewhere) and identify opportunities and barriers to manage them at a regional or global level – which could then be shared with counterparts at such levels to reveal issues of common concern. Tracking transboundary risks could also be **integrated** into the **monitoring** and **evaluation** frameworks of **NAPs** to prompt horizon-scanning of risks (and responses) emanating outside a country's borders, as well as the development of effective indicators (Benzie 2014).

One of the challenges for effective transboundary risk management will be attaining **policy coherence across ministries and sectors**, but the NAP process could provide an opportunity to convene new multi-stakeholder groups (such as the UK's interdepartmental Resources and Risks Working Group) to coordinate activities in that regard – for example, across ministries focused on business and trade and foreign policy – and to weigh-up and clarify responsibilities as well as concrete policy implications (such as in trade priorities or economic instruments) (Challinor et al. 2017, Benzie 2014, Defra 2013). Such groups could investigate the impact of transboundary transmission mechanisms and dependencies on their level of climate vulnerability and conversely how they be might be harnessed to strengthen resilience (Benzie and John 2015). **Local authorities** could adopt similar assessments at more micro scales and could play a seminal role in driving innovation in effective policy responses to transboundary climate change risks and in the transfer of knowledge and expertise (see below). In PWC's (2013: 7) UK assessment as well as EYs (2018) Norwegian assessment, they recommended a number of national policy responses – including some of those noted above, but also accounting for transboundary risks in national strategic planning processes, regularly monitoring and testing responses, and initiating mechanisms to identify 'tipping points' which "trigger significant changes to adaptation responses in the UK or globally".

Governments could also evaluate the i**mpacts of their national adaptation actions** on levels of regional or global resilience – as an opportunity to perhaps secure additional climate finance or generate good will – and explore appetite and demand for regional cooperation – joint impact assessments for instance, or complementary adaptation planning with strategic allies and partners (Davis et al. 2016). These could even be formalised into bilateral agreements "with countries that may transmit risk or offer positive adaptation spill overs" (Benzie and Persson 2019: 384). Regional bodies and intergovernmental organisations could even play a role brokering and monitoring such agreements and potentially move beyond the constraints of their traditional role as a conduit of information-sharing and knowledge exchange to develop transboundary assessments, regional agreements and transnational governance arrangements (Benzie and Persson 2019). More informal mechanisms may also be initiated to encourage joint learning (Benzie and Persson 2019). Regional/supra-national plans – such as the EU Adaptation Strategy and Green New Deal – also offer concrete opportunities to advance transboundary risk assessment and management as well as policy alignment/coherence between nation states. Not forgetting all the GHG transfer mechanisms (clean development mechanisms) within the EU or between EU countries and low-GDP countries, which have accompanied mitigation policies with varying degrees of success (Karsenty and Pirard 2007).

Other non-state actors

Finally, the literature review revealed a number of other opportunities for non-state actors to advance the effective governance of transboundary climate change risks. Wei and Chase (2018) propose a series of actions multinational companies can take to reduce risk across their international supply chains – from structured assessments, to actions internally and with suppliers and partners, to the creation of targets and monitoring, evaluation and reporting systems. Benzie and Persson (2019) also identify opportunities to engage investors (assessing transboundary risks to international financial flows) and civil society organisations (who could champion adaptation as a global public good and also play a role in revealing some of the impacts of transboundary risks on the poorest and most vulnerable).

The demonstrable array of opportunities to better manage transboundary climate change risks – via concrete policy processes and stakeholder-driven activities – is encouraging, provided the issue can rise sufficiently up the agenda. A range of regular convening moments – from the UNFCCC intersessional and COP to the NAP Expo and Adaptation Futures Conference – will be critical to leverage in this regard. Events taking place outside the field of climate change will also be relevant (perhaps even more so, given the implications of this agenda for ministries and sectors beyond the usual suspects).

Addressing TCCR at the sub-national level of governance

Addressing global environmental problems

Research on local environmental policy have shown that it is **challenging** to translate **global** and often **diffuse** problems into a **local context** that makes them **understandable** and **relevant** for **local policy actions**. For example, Naustdalslid (1994: 22) points out - based on a broad study of a Norwegian government reform that introduced earmarked funding for employing a full-time environmental officer inn all Norwegian municipalities as from 1990 – that “it is **hard** to imagine that **local** governing bodies can act as drivers in addressing **global** environmental problems”, partly because “the **municipalities** prioritize work on issues that give visible **local** benefits. ”(Op.cit). As a summary of these points, Naustdalslid concludes that this builds up under a thesis "if one wants **local** governments to give superior **priority** to address **global** environmental problems, this can only happen through a minimum of t**op-down pressure** from **national** governments" (ibid. p.23). He also points out that "an environmental policy reversal operation required changes in people's values and priorities" (ibid. p. 25).

On the other hand, since the 1990s we have witnessed an **‘explosion’** in **local** authorities addressing the global task of **reducing greenhouse gas emissions** (Aall et al, 2007; Rudolf 2016; Fuhr et al, 2018). Furthermore, local authorities have also proven to advocate in international negotiations for more ambitious GHG mitigation goals than their respective national governments (Lindseth, 2004).

Consequences of **local** climate change, like an increase in the risk of weather-related **natural hazard events**, could be framed as a **‘local’** environmental problem, cf. the point made by Naustadalslid that this is the type of environmental problems that are typically addressed in local climate policy. Thus, we also find **numerous** examples of **local policy** initiatives to address the risks of **local climate change** – some of which have taken place even before the development of national climate change adaptation strategies (Aall et al, 2012; Granchamp Florentino, Rudolf 2011). And so far, more in line with the observations of local environmental policy presented by Naustdalslid (1994), very **few** examples exist of **sub-national** governments explicitly embracing the challenges of **TCCR**. In fact, the issue of TCCR was the part of the broader climate change adaptation discussion that was assessed as **least** interesting to attain more knowledge about selected among the following categories (in addition to TCCR): Local risks from local climate change, impacts of local climate change on my institution, how societal change may affect the exposure to climate change impacts for the case of my institution, measures my institution can implement in order to reduce negative impacts of climate change, and which government policies can implement in order to reduce negative impacts of climate change in my institution.

Still, we have come across some **few** examples – most of which through the research and development projects conducted in Norway since the start of this area of research around 2005 (cf. an early review of this in Aall, 2012).

<u>Addressing TCCR at the local level: An early example from 2009 for the city of Fredrikstad (Norway)</u>

The review revealed one study that exclusively has investigated TCCR at a local level. initiative was **initiated** by the municipality, and was further on done at a very early stage of evolving a sort of TCCR theory (Sælensminde et al., 2009) as well (for the case of the country in question – Norway) an early stage of putting climate change adaptation a such on the national political agenda (Aall, 2012). The question asked in the study was "what can climate change impacts taking place elsewhere in the world imply for a Norwegian municipality". This study also included the possible effects of an increased ambition level in international greenhouse gas mitigation policies, including that of "peak oil" to occur either as a result of GHG mitigation policies or simply because oil and fossil gas reserves run out.

The study shows that for Fredrikstad municipality might expect the following **TCCR related challenges**:

- Increase in '**climate refug**ees' (remember, thus was prior to the situation in Syria)
- Increased value of **local cultivated and arable land** due to reduced global food production, and an increased importance in strengthening national (and local) food self sufficiency
- Reduced person- and freight **mobility** because of "peak oil" and tougher GHG mitigation policies, and thus more weight on densification as a land-use planning strategy
- Reduced access to **low-price imported soy-based fodder** to local fish farming and meat production
- Global **increase** in the **demand** for **renewable energy**, thus increasing the value of local resources that can be used to produced energy (wind, hydro, bio etc)
- Increased/decreased **tourism** and business travels depending on the development of pull-factors (e.g. reduced snow-reliability in competing tourism markets abroad) versus push-factors (e.g. less favourable summer-climate in Norway)

The study concludes by presenting a **framework** for how local authorities can address TCCR and include this aspect in their climate change adaptation work, taking as a starting-point a framework presented in a Canadian handbook on local climate change adaptation: The climate vulnerability-emission dual table (Bizikova et al, 2008):

1. Identify **interests** locally that may be affected by the consequences of climate change elsewhere in the world
2. Describe the possible **chains of interaction** (economically or otherwise) that may link local interests that might be at stake with climate change related situations abroad.
3. Link each of the identified interests that are potentially at risk and the corresponding chains of interaction with corresponding **critical geographical locations** abroad (e.g. origin of imported goods, critical transport node).
4. For each identified critical geographical location consider how climate change in interaction with societal change may create **risks**, and how such risks may affect local interests.
5. Analyse possible **local actions** that can reduce the identified risks.

This approach has later been tested in an additional Norwegian city: Stavanger.

Addressing TCCR at the county level: An example from 2017 for the county of Sogn og Fjordane (Norway)

In 2016 the project "Cooperation for a green shift" commissioned by the **county of Sogn og Fjordane** was initiated, which involved the County Governor in Sogn og Fjordane, the Western Norway branch of the Norwegian Public Roads Administration Region and of the Norwegian Water Resources and Energy Directorate, and in addition **9 municipalities**. The main goal of the project was to strengthen the knowledge of conditions for societal transformation in the face of climate change at the county and local level of government. Furthermore, the project was aimed at establishing a wholistic approach to climate change policy, and to increase the capacity of public policy actors at the county level to support the local level of government in developing wholistic climate change strategies and action plans. This work also including the issue of TCCR.

The **first** stage of the project was to create a knowledge base analyse climate change risks for the case of Sogn and Fjordane. A co-production approach was used, in which the involved researchers combined insights derived from research literature and relevant national databases with knowledge derived through systematic group interviews of representatives from the involved county actors, and documenting this in an extensive report (Aall, Groven, Kvamsås, 2017). A separate chapter was devoted to TCCR, and an overarching analytical framework was developed to assist policy stakeholders in identifying relevant transboundary climate risks (see table below). The key to this was to differentiate between different categories of **interests** and different ways climate risks can be mediated through society **'streams of risk**'.

Table 10 *Framework used for the case of Sogn og Fjordane county to analyse sub-national manifestation of transboundary climate change risks (Aall, Groven, Kvamsås, 2017*

Main category of interests	Subcategory of interests	Streams going out of Norway	Streams going into Norway
People and companies	Tourism	Norwegians abroad	Foreigners in Norway
	Persons with permanent residence permits	Norwegians living abroad	"Climate refugees" to Norway
	Persons applying for work permits	Norwegians abroad	Labor immigration
	Companies	Norwegian companies abroad	Foreign enterprises in Norway

Goods, services and public transfers	Energy	Exports of oil, coal and gas	Import of energy
		Exports of renewable energy	
	Food	Exports of food products	Import of food products
	Transport	Transport through Norwegian territory	Transfer to Norway
		Transport out of Norway	Transfer to Norway
	Other goods and services	Norwegian development aid	Import of other goods and services
		Norwegian Foreign Trade	
		Other Norwegian exports	
Resources outside of an economic market	Disease organisms	Infection of Norwegians abroad	Introduction of new disease promoting organisms
	Other living organisms	Exodus from Norway	Immigration to Norway
	Pollution	Increased spread from Norway	Increased introduction to Norway

The group interviews of representatives from the involved county actor highlighted the following climate risks that might affect Sogn og Fjordane:

- Increase in "climate change related" **immigration**, which could be positive since Sogn og Fjordane is suffering from reduced population growth. On the other hand, based on the local experiences from handling the high number of Syria-refugees coming to Norway (and the county of Sogn og Fjordane), a situation with high numbers of climate change induced immigration will put **pressure** on the local communities with respect to integration.
- Negative economic development in other countries due to the climate change, which could negatively affect inbound **tourism** to Sogn og Fjordane.
- Reduced **global food security** due to climate change can increase the local value of cultivated and arable land, thus putting more **restrictions** on local land-use development for other purposes and at the same time be economically **beneficial** for local farmers.
- Reduced supply of **imported soy and corn** for producing **fodder** for Norwegian livestock may affect negatively local farmers in Sogn og Fjordane, and force farmers to utilize better the **existing resources for mountain grazing.**
- A possible increase in the 'import' of new climate change induced diseases can increase the **pressure** on the capacity of **local health care**.

The **second** stage of the project was to facilitate that the knowledge basis described above would be addressed in ongoing **planning processes**.

An assessment of the **county** climate plan of Sogn og Fjordane that was developed parallel to and in direct dialogue with the "green shift project" (and which happened to be the first county plan in Norway to use the term "societal transformation" in the title instead of traditional terms like "climate action" or "climate policy") showed however **no** mentioning of TCCR (Aall, 2019).

7 of the involved 9 municipalities adopted one or more **local plans** of some sort that made use of the knowledge basis developed in the "green shift" project, but **none** of these addressed actively TCCR. However, **one** plan which comprises four of the municipalities that took part in the "green shift" project (newly merged into one municipality) addressed TCCR **indirectly**, by stating the following **goal**:

"By 2030 we have knowledge of local vulnerabilities to climate change taking place in other countries and we have adopted measures to reduce / minimize the impact of these vulnerabilities"[18].

Implicit sub-national adaptation to TCCR

As described above, using Norway as a case, there are very few signs of explicitly addressing TCCR at the sub-national level of government. However, there are some signs of **implicitly** doing so – in other words to address locally challenges that also could also be framed as a TCCR-related challenge - still using Norway as an example.

When looking closer at the national guidance notes for land-use planning in Norway, the government show high consistency in prevailing cultivated and arable land for agriculture. In 2015 the Parliament decided to strengthen the law to protect cultivated and arable land from urban development[19]. Using reduced global food security caused by climate change as an argument, the state is currently expecting **sub-national** levels of governments to **strengthen** their efforts to **protect cultivated and arable land**.

Also, **tourism** can serve as an example of implicit sub-national adaptation to TCCR. Inbound tourism is an important business sector in many rural communities in Norway. There are numerous studies on how climate change will affect tourism in general or at specific locations (e.g. impacts in the Alps of reduced snow-reliability), but very few studies looking specifically of **cross border impacts**, except for border regions such as the Upper Rhine. The stations on both sides of the Rhine compare themselves carefully, thus assessing the attractiveness of their adaptation measures to the reduced snow cover. This reciprocal observation does not always include studies on a larger scale, i.e. between the Alps and the Vosges and Black Forest massifs (Scholze, Glazer, Roy 2018). The impacts of climate change in different tourism markets and destinations may change global tourism travel patterns. One study that on a very general level has done such analysis concludes in the following way (Scott, Hall and Gössling, 2019)

- **Lowest** climate change vulnerability for tourism is found in **higher-latitude OECD countries**
- **Highest** climate change vulnerability often coincides with the **highest sector GDP contribution**
- **Highest** vulnerability exists in regions where **tourism growth** is expected to be the **strongest**
- Climate change will pose an increasing **barrier** to tourism contributions to reach the United Nations Sustainable Development Goals (**SDGs**)
- Consideration of **climate change** should be strengthened in **tourism development plans**

Going back to Norway, this might – at least in the short and medium run – look **good** for tourism destinations in Norway. Reduced snow reliability in competing markets, like the Alps, and still good conditions in Norway can trigger a double positive effect: Foreign tourists leaving e.g. the Alps and coming instead to Norway as well as Norwegian tourists doing the same. And Norwegian winter tourism is preparing for this to happen, by means of currently **increasing** heavily the capacity of **artificial snow production** at major ski resorts (Scott et al, 2019).

18 https://sunnfjord.kommune.no/_f/p1/i58d3e39e-c360-45ff-9f05-9a3c586e415e/plan-og-kunnskapsdel-interkommunal-plan-for-klimaomstilling-vedtatt-juni-2019.pdf

[19] https://www.stortinget.no/globalassets/pdf/innstillinger/stortinget/2015-2016/inns-201516-056.pdf

Cross-border nature management

Nature management and policy challenges related to up-stream and down-stream are well known in the literature, both in a direct physical sense (e.g. management of rivers) and figurative sense (e.g. life cycle analysis of environmental impacts). Of relevance in this context is the management of climate change risks relating to **rivers** when they are crossing borders. De Jong, Snelder and Ishikawa (2010, p. 3) precise that: "River systems, for instance, have been subject to binational or multinational coordination between countries for many decades (…). Transboundary governance of river systems have recently received a new impetus, because countries have become more aware and sensitive about upstream influences on water quality and flooding regimes, but also because factors such as climate change are expected to modify frequency and intensity of flooding in river systems (…) ».

The management of the **Upper Rhine Region** can serve as an example. This region is characterised first of all by its longstanding integrated European character, both from the point of view of managing major internal security and economic issues such as access to water and logistics on the Rhine and because of its cross-border territories which are often nature reserves (forests, wetlands, reservoirs of biodiversity, etc.) (Guy 2019).

Concerning the Rhine River some agreement was conclude in the early 1800s between the French and German empires in order to regulate trade. The CCNR was founded in 1804 and consolidated by the Treaty of Paris of 30 May 1814, which lays down the principle of freedom of navigation on Europe's major international rivers. The institution has undergone various changes of direction until recently, when it specialised in navigation issues on a European scale and not strictly on the Rhine[20]. The same applies to the ICRP, which deals with the protection of the Rhine. The latter has known an important turn after the Sandoz catastrophe in 1986[21] (De Jong, Snelder and Ishikawa 2010).

As we have already indicated, navigation on the Rhine is part of a long history that has been overtaken by the protection of the Rhine as an ecosystem and habitat, a functionality of the Rhine that gained massive social recognition following the major accident at Sandoz in 1986 (Theys and Fabiani 1987; Roqueplo 1988 and Roqueplo 1992). The international coordination bodies (CCNR for the navigation on the Rhine, extended to the navigation in the EU and the ICPR, which reached a turning point following the Sandoz accident and whose involvement in the climate field has been growing since 2003) attempt to find concerted responses to the various hazards constrained by climate change as floods and water level (Woehrling 2008; Kriedel 2015).

In their alternation, low and highwater levels define a 'normal' cycle of the river's life. For comparison, this alternation is equivalent to the greenhouse effect, which occurs the conditions of life on earth. On the other hand, the evolution of their profile (water level, duration) may differ from current values. As in the case of floods, periods of low water levels occasionally experience exceptional fluctuations (centennial floods, exceptional low water levels, etc.). These situations are also "normal". On the other hand, when certain thresholds and frequencies are reached and these extreme events return, we can speak of an intensification of the hazards. Intensity and frequency of the floods and water level are indicators of climate change for the Rhine River. From the point of view of the

[20] https://www.ccr-zkr.org/

[21] https://www.iksr.org/).

evolution of climatic hazards likely to exert stresses on the human activities, it is essentially the state of the water reservoirs and its temperature, which configure the climatic stress situations. Water reservoirs are impacted by rainfall (overall quantity and seasonal distribution) on the one hand, and by the amount of snow cover (which depends on winter temperatures) and the amount of glacier melting (which also depends on seasonal temperatures) on the other. (Stahl et al. 2016). In addition to these hazards and in accordance with the cascade effects (Lagadec 1981; Godard et al. 2001), the local flood management contribute also to the construction of risk, i.e. to the vulnerability of the territories and the human activities. The numerous reports unanimously conclude that the social interdependency of the river has increased its vulnerability in many ways, excepting the development of water sanitation systems and probably the monitoring and warning systems, due to the long history of international cooperation, which seem to have reduced it.

In addition to the periods of low and high water levels, the state of the water temperature is an aggravating factor in situations of low water levels. The association of a low-water period in summer with high temperatures (heat waves, heat waves, drought) increases the risk of biological stress as well as the security of power plants and dikes in the case of the Rhine River. (Görgen et al. 2010).

Unlike floods, which are one-off events and do not impact the system as a whole, the period of low and high water levels concerns the entire system, even if in a contrasting manner and staggered over time. On the scale of the Rhine River, the effects of climate change meet the increased social demands linked to the intensification of activities that depend on the river[22]. Social vulnerability to climatic hazards is a function here of the increase in social dependence on rivers, so there is an increase in vulnerability by the intensification of certain hazards and by the increase in activities that depend on the river (Rudolf 2009 and Rudolf 2015). This dependence extends far beyond the river's course because of the many territories that depend on it. (Arbeitskreiz KLIWA, 2017). The Rhine indeed crosses several countries of the European Union and is connected to more countries by its numerous tributaries and effluents that link it to other regions that are not strictly bordering (ICPR 2018).

Despite their specificities, the territories relying on the Rhine River have organised themselves in response to this "commonality". Consequently, they have work out technical, political, administrative, economic, etc. responses to manage this common good. The governance rests nowadays on stabilised knowledge, adjusted methods, information practices and reciprocal intelligence. All these resources contribute to typify this TTCR as what the risk literature describes as known risks, as opposed to new risks (Godard et al. 2001). This classification doesn't exclude the existence of uncertainties, due to complexity and tight coupling (Perrow 1984), but considers that the social recognition of a risk through regular practices like measurements, flows of information, etc.

[22] From energy production (thermonuclear, but also hydroelectricity, coal-fired power stations, etc.), navigation on the Rhine and the transport of goods with sectors preferentially impacted such as metallurgy, agrifood, construction and public works, agriculture, etc. but also the tourism sector (navigation on the Rhine, cruises, etc.).

make a difference in the management of complexity and tight coupling[23]. The Rhine River therefore illustrates perfectly the large scale of trigger that can frame a TTCR. Resulting from shock event, slow hazard as well as the reflexion of some mitigation and adaptation policies they can be described as well as neighbour risks or 'cross-border' risk (Perman 2003)[24] as well as trans-national and globalized ones.

Conclusions

Despite sophisticated governance structures initiated to manage adaptation at a sub-national, national and supra-national levels of governance, the concept of transboundary climate change risk and the benefits of a scaled approach to adaptation **any** of these three levels are **yet to be widely recognise**d (Benzie and Persson 2019, Benzie et al. 2016). The assessments that have taken place have generated **few** tangible policy recommendations for how to adapt to transboundary climate change risks and even more limited responses and there are **significant outstanding questions regarding who 'owns' such risks** (Benzie and Persson 2019, Benzie et al. 2016). As Benzie and Persson (2019: 375) note, we are left with a paradox: "on the one hand, climate change is held up as the archetype of a truly 'global' problem… and yet, the problem that we need to adapt to is usually seen as a local phenomenon, or locally manifested". This 'blind spot' of climate change adaptation is clearly **weakest** at the **sub-national** level of governance, given the imbalance in studies that exist giving far the most attention so far to the national and sub-national levels of governance.

The review presented in this chapter has revealed some of the challenges to policy uptake that might be limiting factors, acknowledging but also moving beyond the pervasiveness of the norm that Benzie and Persson note:

- A series of factors that **limit** the capabilities of policymakers to address transboundary risks – including several **knowledge** gaps but also (and perhaps overlooked) **skill** and **capacity gaps** – despite several exploratory advances to drive conceptual clarity, design classification systems and invent robust methodologies in recent years;
- An arguably even more **fundamental series of challenges** in **motivating policymakers** to **account** for transboundary risks, given the lack of clarity about who is accountable for managing such risks and the lack of tailored arguments and incentives developed to motivate different stakeholder groups (which will be crucial given the inherent complexity of the topic, the 'hiding in plain sight' nature of transboundary risks and the political and normative factors incentivising a territorial view transboundary); there are perhaps opportunities to learn from

[23] Starting from the distinction made between known risks and probable risks (Wynne, ; Theys ...; Godard et al.;),. This distinction is based on the importance of the production of knowledge, particularly grey knowledge, associated with the identification of relevant variables, the implementation of regular hazard recording systems, and efforts to harmonize units, indicators and methodologies. All these practices, which are as much a matter of administrative sciences as of academic sciences, contribute to the construction of known risks. Thus risks that have been monitored for a long time are not at the same level of apprehension and intelligibility as risks that do not have a full administrative, political and scientific context. This is the case of the risks associated with floods and low water levels on the Rhine, which existed independently of the climate issue, but which this new issue has reconfigured.

[24] Perkman uses the term 'cross-border region' to reflect an area that is subject to some coordinated transboundary governance.

the nascent demand for transboundary risk assessments from policymakers to date to better understand who has initiated and utilised these and whether lessons can be learnt to encourage wider uptake;

- A promising **array of policy windows** and **concrete opportunities** to seed transboundary climate change risks into relevant policy agendas and organisational processes – revealing several opportunities to harness should capabilities become refined over time and incentive structures aligned. Still, these windows of opportunity are so far most seen on the **national** and **supra-national** levels of government, leaving the sub-national level almost free of any initiatives pointing in the direction of how to address transboundary climate change risks also at the lowest level of governance.

The UNCHAIN case studies will undoubtedly strengthen the evidence-base on transboundary climate change risk in identified countries and for relevant sectors, particularly if they advance the knowledge-base by addressing some of the identified gaps this review revealed and thus increase the capability of policymakers to act on their findings when synthesised with evidence from the wider field. The review also indicates that there are likely to be identifiable **policy windows** and **processes** within which findings can percolate and inform the design of policy responses – from the local to the national to the global level – which can be mapped and used to inform the timings and approach of concrete deliverables. But articulating and framing the findings in such a way so as to develop propositions that increase the motivation of identified and targeted policymakers to respond will also be important – exploring questions of governance and ownership, the political economy of risk management, the kinds of implementable policy recommendations that could effectively strengthen resilience to such risks and the existing national or regional policies that they could be directed towards. In such a way, the case studies could substantially advance the state of the debate on transboundary climate change risk.

References

Aall, C. (2012): The early experiences of local climate change adaptation in Norwegian municipalities compared with that of Local Agenda 21 and climate change mitigation, Local Environment: The International Journal of Justice and Sustainability, 17:6-7, 579-595

Aall, C. (2019): Sluttrapport frå prosjektet «Samhandling for grønt skifte» VF-repport 10/2019. Sogndal: Vestlandsforsking (In Norwegian. English translation of title: “Final report from the project ‘Cooperation for a green shift’”). Retrieved from https://www.vestforsk.no/sites/default/files/2019-10/R-KO-sluttrapport%20%281%29.pdf

Aall, C., Groven, K., & Kvamsås, H. (2017). Det grøne skiftet . Heilskapleg sårbarheitsanalyse for Sogn og Fjordane Bakgrunnsnotat for utarbeiding av lokale analysar Vestlandsforsking rapport (In Norwegian. English translation of title: "The green change. Analysis of vulnerability for Sogn og Fjordane) Retrieved from https://www.vestforsk.no/sites/default/files/2017-04/VF-rapport%205-2017%20Det%20gr%C3%B8ne%20skiftet.pdf

Aall, C., Groven, K., Lindseth, G. (2007): The scope of action for local climate policy: the case of Norway. Global Environmental Politics, Volume 7, Number 2: 83-102.

Aall, C., Kanyama, A. C., Hovelsrud, G. (2012): Local climate change adaptation: missing link, Black Jack or blind alley? Local Environment: The International Journal of Justice and Sustainability, 17:6-7, 573-578.

Akrich M., Callon M., Latour B. (2006): Sociologie de la traduction. Textes fondateurs. Presses de l'Ecole des Mines. Paris.

Arbeitskreis KLIWA (2017): Seite und Projekt über Niedrigwasser-Anpassung

Averbeck P., Frör O., Gartizer N., Lützel N., Rudolf F. (2019): Climate change preparedness of enterprises in the Upper Rhine region from a business perspective- A multidisciplinary, transboundary analysis. Nachhaltigkeits Management Forum, 27, pp. 83-93.

AWBI (2019). Transboundary climate risks: an overview. ODI, SEI and IDDRI. https://adaptationwithoutborders.org/sites/weadapt.org/files/2017/transboundary_climate_risks_web.pdf

Becerra S. & Peltier A. (eds.) (2009): Risques et environnement: recherches interdisciplinaires sur la vulnérabilité des sociétiés. L'Harmattan. Paris

Beck U. (1986): Risikogesellschaft. Auf dem Weg in eine andere Moderne. Suhrkamp. Frankfurt/Main

Belz J. (2005): Niedrigwasser-Abflüsse im Rheingebiet im 20. Jahrhundert –Veränderungen und Ursachen. – In: BfG-Veranstaltungen 5/2005 „Erfahrungen zur Niedrigwasserbewirtschaftung", Koblenz.

Belz, J., Brahmer, G., Buiteveld, H., Engel, H., Grabher, R., Hodel, H., Krahe, P., Lammersen, R., Larina, M., Mendel, H. G., Meuser, A., Müller, G., Pfister, L. Plonka, B. und W. van Vuuren (2007): Das Abflussregime des Rheins und seiner Nebenflüsse im 20. Jahrhundert – Analyse, Veränderungen, Trends. KHR-Bericht Nr. I-22, ISBN 978-90-70980-33-7.

Benzie, M. (2014). National Adaptation Plans and the indirect impacts of climate change. SEI policy brief. Stockholm Environment Institute: Stockholm.

Benzie, M. and Bessonova, E. (2018). Inescapably intertwined: the reality of globalisation and borderless climate risks. Story. Stockholm Environment Institute: Stockholm.

Benzie, M. and Persson, Å. (2019). Governing borderless climate risks: moving beyond the territorial framing of adaptation. International Environmental Agreements: Politics, Law and Economics.

Benzie, M., Adams, K.M., Roberts, E., Magnan, A. K., Persson, A., Nadin, R., Klein, R.J.T., Harris, K., Treyer, S. and Kirbyshire, A. (2018). Meeting the global challenge of adaptation by addressing transboundary climate risk: A joint collaboration between SEI, IDDRI, and ODI. Discussion Brief. Stockholm Environment Institute, Stockholm.

Benzie, M., and A. John (2015). Reducing vulnerability to food price shocks in a changing climate. SEI Discussion Brief. Stockholm Environment Institute: Stockholm.

Benzie, M., Hedlund, J., & Carlsen, H. (2016). Introducing the Transnational Climate Impacts Index : Indicators of country-level exposure – methodology report. Retrieved from https://www.sei.org/wp-content/uploads/2016/06/introducing-the-transnational-climate-impacts-index-indicators-of-country-level-exposure-methodology-report.pdf

Benzie, M., J. Hedlund and H. Carlsen (2016). Introducing the Transnational Climate Impacts Index: Indicators of country-level exposure – methodology report. Working Paper 2016-07. Stockholm Environment Institute: Stockholm.

BfG (Bundesanstahlt für Gewässerkunde) (2016): Informationsplattform Undine (u.a; Seite „Extremereignisse Rhein: Hochwasser, Niedrigwasser"). http://undine.bafg.de/

Bizikova L., T. Neale and I. Burton 2008. Canadian communities' guidebook for adaptation to climate change. Including an approach to generate mitigation co-benefits in the context of sustainable development. First Edition. Environment Canada and University of British Columbia, Vancouver.

Buan, I. F., Inderberg, T. H. J., & Rottem, S. V. (2010). Globale og regionale følger av klimaendringer (In Norwegian. English translation of title: "Global and regional consequences of climate change. Consequences for Norway. Report to the Committee on the Government Green Paper on Climate Change Adaptation). Retrieved from https://www.regjeringen.no/globalassets/upload/md/vedlegg/klima/klimatilpasning/underlagsrapporter/fni_rapport_klimatilpansing_2010.pdf

Challinor, A. J., Adger, W. N., & Benton, T. G. (2017). Climate risks across borders and scales. Nature Climate Change, 7(9), 621–623.

Chen, B., Han, M.Y., Peng, K., Zhou, S.L., Shao, L., Wu, X.F., Wei, W.D., Liu, S.Y., Li, Z., Li, J.S., Chen, G.Q. (2018): Global land-water nexus: Agricultural land and freshwater use embodied in worldwide supply chains. Science of The Total Environment, 613–614, pp. 931–943.

CIPR (2013b): Etat des connaissances sur les éventuelles repercussions de modifications du regime hydrologique et de la temperature de l''eau sur l'écosystème du Rhin et actions envisageables. 204. https://www.iksr.org/

CIPR (2018): Inventaires des étiages Rhin, 248.

Ciscar JC. Feyen L, Soria A, Lavalle C, Raes F, Perry M, Nemry F, Demirel H, Rozsai M, Dosio A, Donatelli M, Srivastava A, Fumagalli D, Niemeyer S, Shrestha S, Ciaian P, Himics M, Van Doorslaer B, Barrios S, Ibáñez N, Forzieri G, Rojas R, Bianchi A, Dowling P, Camia A, Libertà G, San Miguel J, de Rigo D, Caudullo G, Barredo JI, Paci D, Pycroft J, Saveyn B, Van Regemorter D, Revesz T, Vandyck T, Vrontisi Z, Baranzelli C, Vandecasteele I, Batista e Silva F, Ibarreta D (2014): Climate Impacts in Europe. The JRC PESETA II Project. JRC Scientific and Policy Reports, EUR 26586EN.

Commission de l'UE (2007): Communication – Faire face aux problèmes de rareté de la resource en eau et de sécheresse dans l'Union européenne (COM/2007/0414). https://eur-lex.europa.eu/legalcontent/FR/TXT/?uri=CELEX%3A52007DC0414 http://ec.europa.eu/environment/water/adaptation/index_en.htm

Commission de l'UE (2008): Technical Report 023 - Drought management plan report including agricultural, drought indicators and climate change aspects (Water scarcity and droughts expert network) http://ec.europa.eu/environment/water/quantity/pdf/dmp_report.pdf

Cournil, C. (2010) : Les "réfugiés environnementaux" : enjeux et questionnements autour d'une catégorie émergente. Migrations Société, 128(2), pp. 67-79.

Davis, M., M. Benzie and J. Barrott (2016). Transnational climate change impacts: An entry point to enhanced global cooperation on adaptation? SEI policy brief. Stockholm Environment Institute: Stockholm.

De Jong W., Snelder D., Ishikawa N. (eds), (2010). Transborder governance of forests, rivers and seas. Oxon, New York, Earthcan, Routledge.

Defra (2013). The National Adaptation Programme: Making the Country Resilient to a Changing Climate. Presented to Parliament pursuant to Section 58 of the Climate Change Act 2008. UK Department for Environment, Food and Rural Affairs, London.

Defra (2018). The National Adaptation Programme and the Third Strategy for Climate Adaptation Reporting: Making the Country Resilient to a Changing Climate. UK Department for Environment, Food and Rural Affairs, London.

Dellink, R., Hwang, H., Lanzi, E., Chateau, J. (2017): International trade consequences of climate change. OECD Trade and Environment Working Papers 2017/1, OECD Publishing.

Distelkamp, M., Meyer, M. (2019): Pathways to a Resource-Efficient and Low-Carbon Europe. Ecological Economics, 155, pp. 88–104.

Domenach, H., Gonin, P. (2002), Revue européenne des migrations internationales, vol. 18 - n°2.

Domenach, H., Picouet, M. (1995) : Les migrations, Que sais-je ? n°224.

Douglas M., Wildavsky A. (1982): Risk and Culture. University of California Press.

El-Hinnawi Essam (1985) : Environmental Refugees, Nairobi, UNEP.

Emelianoff C. (2013): Local Energy Transition and Multilevel Climate Governance. Lessons from two Pioneer Cities (Hanover, Germany, and Växjö, Sweden). Urban Studies.

Emelianoff, C. (2007) : La ville durable : l'hypothèse d'un tournant urbanistique en Europe. L'Information géographique, vol. 71(3), pp. 48-65. doi:10.3917/lig.713.0048.

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin and J. Rockstrom (2010). "Resilience thinking: integrating resilience, adaptability and transformability." Ecology and Society 15(4): 20

Foresight International Dimensions of Climate Change (2011): International Dimensions of Climate Change. Final Project Report. The Government Office for Science, London.

Fuhr, H., Hickmann, T., Kern, K. (2018): The role of cities in multi-level climate governance: local climate policies and the 1.5 °C target. Current Opinion in Environmental Sustainability, Volume 30, Pages 1-6

Galli, A., Iha, K., Halle, M., El Bilali, H., Grunewald, N., Eaton, D., Capone, R., Debs, P., Bottalico, F. (2017): Mediterranean countries' food consumption and sourcing patterns: An Ecological Footprint viewpoint. Science of The Total Environment, 578, pp. 383–391.

Gauchard F. Hattenberger A.-M. (2005): Rapport sur l'évaluation du risque d'apparition et de développement de maladies animals compte tenu d'un éventuel changement climatique. Paris: Documentation Française.

Gemenne, F. (2008) : L'environnement comme facteur migratoire : réflexions croisées sur deux études de cas empiriques à Tuvalu et à la Nouvelle-Orléans, communication présentée au séminaire de l'École doctorale thématique « migrations et Diversité culturelle », Louvain-la-Neuve. http://www.cedem.ulg.ac.be/m/cdc/15.pdf

Giljum, S., Bruckner, M., Martinez, A. (2015): Material Footprint Assessment in a Global Input-Output Framework. Journal of Industrial Ecology, 19, pp. 792–804.

Gobert J. , Rudolf F., Kudriavtsev A., Averbeck P. (2017): L'adaptation des entreprises au changement climatique. Questionnements théoriques et opérationnels. Revue d'Allemagne et des pays de langue allemande. 49-2, pp. 491-504.

Godard O., Henry C., Lagadec P. and Michel-Kerian E. (2002): Traité des nouveaux risques. Gallimard. Paris.

Goldstein, A., Turner, W. R., Gladstone, J., & Hole, D. G. (2019). The private sector's climate change risk and adaptation blind spots. Nature Climate Change, 9(1), 18–25. https://doi.org/10.1038/s41558-018-0340-5

Görgen K. et al. (2010): Assessment of Climate Change Impacts on Discharge in the River Rhine Basin. Results of the RheinBlick2050 project. KHR-Bericht Nr. I-23, ISBN 978-90-70980-35-1.

Granchamp Florentino F., Rudolf F. (2011) : La percolation du changement climatique : de la planète au quartier. Labranche S. (eds.) (2011): Le changement climatique. Du méta risque à la méta gouvernance. Lavoisier, pp. 15-34.

Groven, K., Aall, C., & Dannevig, H. (2016). Planning for climate change vulnerability? Paper Presented at the 4th Nordic Conference on Climate Change Adaptation 2016.

Guy E. (2019) Diplomatie territoriale scientifique et coopération transfrontalière franco-germano-suisse Revue des Relations Internationales, 3, N°179, pp. 83-94.

Hallegatte, S. (2015): The Indirect Cost of Natural Disasters and an Economic Definition of Macroeconomic Resilience. Policy Research Working Paper 7357, The World Bank.

Hedlund, J., Fick, S., Carlsen, H. and Benzie, M. (2018). Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk. Global Environmental Change, 52, 75-85.

Hedlund, J., Fick, S., Carlsen, H., & Benzie, M. (2018). Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk. Global Environmental Change, 52, 75–85. https://doi.org/10.1016/j.gloenvcha.2018.04.006Khan, M. R. (2013). Toward a binding climate change adaptation regime: A proposed framework (1st ed.). London, New York: Routledge.
Karsenty A., Pirard R. (2007): Changement climatique: faut-il récompenser la "déforestation évitée"?. Natures Sciences Sociétés. 15, pp. 357-369.

Koks, E. E., Thissen, M. (2016): A Multiregional Impact Assessment Model for disaster analysis, Economic Systems Research, 28, pp. 429–449.

Koks, E. E., Thissen, M., Alfieri, L., de Moel, H., Feyen, L., Jongman, B., Aerts, J.C.J.H. (2019): The macroeconomic impacts of future river flooding in Europe. Environmental Research Letters, 14, 084042.

Krey, V. (2014): Global energy-climate scenarios and models: a review. WIREs Energy Environ, 3, pp. 363–383.

Kriedel N. (2015): La navigation fluviale sur le Rhin au XIX[e] siècle. Rudolf F. (eds.) (2015) : Retour sur le modèle rhénan – humanisme, capitalisme et métropolisation. Revue d'Allemagne et des pays de langue allemande. 47-2. pp. 307-320.

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H. & Wilbanks, T. (2012): The need for and use of socioeconomic scenarios for climate change analysis: A new approach based on shared socioeconomic pathways. Global Environmental Change, 22, pp. 807–822.

Lagadec P. (1981): La civilisation du risque. Catastrophe technologiques et responsabilités sociales. Seuil. Paris.

Lagadec P. (2008): Changement climatique et chocs extremes: defies, pièges, pistes. https://hal.archives-ouvertes.fr/hal-00339759.

Langer L., Tripney J. and Gough, D. (2016). The Science of Using Science: Researching the Use of Research Evidence in Decision-Making. London: EPPI-Centre, Social Science Research Unit, UCL Institute of Education, University College London.

Lash S., Szerszynski B. and Wynne B. (eds.) (1996): Risk, Environment and Modernity. Towards a new Ecology. Sage Publications. London.

Lehr, U., Meyer, M., Becker, L., Rome, E., Lückerath, D., Nyadzi, E., Menk, L. (2020): Knowledge review about socioeconomic scenarios and societal exposure to climate change. Report on Task 1.4 of the UNCHAIN project.

Lindseth, G. (2004): The Cities for Climate Protection Campaign (CCPC) and the framing of Local Climate Policy, The International Journal of Justice and Sustainability, Volume 9, Issue 4: 325-336.

Michie, S., M van Stralen, M. and West, R. (2011). The behaviour change wheel: A new method for characterising and designing behaviour change interventions. Implementation Science, 6:42.

Ministère des Affaires étrangères et du Développement international (2017): Diplomatie et territoires, pour une action extérieure démultipliée. La Documentation française. Paris.

Nadin, R. and Roberts, E. (2018). Moving towards a growing global discourse on adaptation. London: ODI.

Naustadslid, J. (1994): "Globale miljøproblem – lokale løysingar". I Jon Naustdalslid og Sissel Hovik (eds) (1994), Lokalt Miljøvern. Oslo: Tano. Naustdalslid, J. og S. Hovik (red) (1994): Lokalt miljøvern. TANO/NIBR, Oslo.

Nelson, D. R., W. N. Adger and K. Brown (2007). "Adaptation to environmental change: Contributions of a resilience framework." Annual Review of Environment and Resources 32: 395-419.

Norwegian official Report NOU. (2010). Tilpassing til eit klima i endring. (In Norwegian. English translation: Adaptation to a changing climate). Retrieved from https://www.regjeringen.no/no/dokumenter/nou-2010-10/id624355/

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R., & van Vuuren, D. P. (2014): A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Climatic Change, 122, pp. 387–400.

OECD (2015): The Economic Consequences of Climate Change, OECD Publishing, Paris.

Okuyama, Y. (2007): Economic Modeling for Disaster Impact Analysis: Past, Present, and Future. Economic Systems Research, 19, pp. 115–124.

Okuyama, Y., Santos, J.R. (2014): Disaster impact and input output analysis. Economic Systems Research, 26, pp. 1–12.

Oosterhaven, J., Bouwmeester, M.C. (2016): A new approach to modelling the impact of disruptive events. Journal of Regional Science, 56, pp. 583–595.

Oosterhaven, J., Többen, J. (2017): Wider economic impacts of heavy flooding in Germany: a non-linear programming approach. Spatial Economic Analysis, 12, pp. 404–428.

Otto, C., Willner, S.N., Wenz, L., Frieler, K., Levermann, A. (2017): Modeling loss-propagation in the global supply network: The dynamic agent-based model acclimate. Journal of Economic Dynamics and Control, 83, pp. 232–269.

Patt, A.G., v. Vuuren, D.P., Berkhout, F., Aaheim, A., Hof, A.F., Isaac, M., Mechler, R., (2010): Adaptation in integrated assessment modeling: where do we stand? Climatic Change, 99, pp. 383–402.

Perkman, M. (2003) 'Cross-border regions in Europe. Significance and drivers of regional cross-border cooperation', European and Urban Regional Studies, vol. 10, pp. 133–171.

Perrow, C. (1984). Normal accidents: living with high-risk technologies. New York, Basic Books.

Perrow, C. (2007). The next catastrophe: reducing our vulnerabilities to natural, industrial, and terrorist disasters. Princeton, N.J., Princeton University Press.

Phatak, A. V. (1995). International dimensions of management. 246.

Prytz, N., Norbø, F. S., Higham, J. D. ., & Thornam, H. (2018). Utredning om konsekvenser for Norge av klimaendringer i andre land. (In Norwegian. English translation of title: "Investigation on the consequences for Norway of climate change in other countries"). In M-932. Retrieved from https://www.miljodirektoratet.no/globalassets/publikasjoner/m932/m932.pdf

PWC. (2013). International threats and opportunities of climate change for the UK. London: PwC.

Rammert, W. (2003) : Technik in Aktion :verteiltes Handeln in soziotechnischen Konstellationen. TUTS – Working Papers, 2-2003. Berlin: Technische Universität Berlin, Fak. VI Planen, Bauen, Umwelt, Institut für Soziologie Fachgebiet Techniksoziologie. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-11573

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Crespo Cuaresma, J., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. & Tavoni, M. (2017): The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions im-plications: An overview, Global Environmental Change, 42, pp. 153–168.

Roqueplo P. (1988): Pluies acides: menaces pour l'Europe. Paris, Economica.

Roqueplo P. (1992): L'expertise scientifique, consensus ou conflit? Theys J., Kalaora B. (eds) (1992): La Terre outrage. Les experts sont formels. Paris, Éditions Autrement. Série Sciences en société, 1, pp. 157-169.

Rothman, D.S., Romero-Lankao, P., Schweizer, V.J., Bee, B.A. (2014): Challenges to adaptation: a fundamental concept for the shared socio-economic pathways and beyond. Climatic Change, 122, pp. 495–507.

Rudolf F. (2012) : La réception territoriale du changement climatique ou comment le changement climatique contribue à l'émergence de territoires et de politiques climatiques spécifiques. VertigO. La revue électronique en sciences de l'environnement. Hors-série 12 (http://vertigo.revues.org/11825)

Rudolf F. (2015) : Les enjeux de la territorialisation des changements climatiques : les épreuves de la montée en compétence des entreprises à travers l'exemple alsacien. Pollution atmosphérique [En ligne], N° 225, mis à jour le : 22/05/2015, URL : http://lodel.irevues.inist.fr/pollution-atmospherique/index.php?id=4842.

Rudolf F. (eds.) (2016): Risques, dangers, vulnérabilités et resilience. Les villes à la croisée des stratégies globales et locales des enjeux climatiques. Les Presses de l'Université Laval. Québec.

Rudolf F., Gobert J. (2019): Les espaces ruraux : entre dépendance et autonomie des métropoles. Le cas du PNR des Vosges du Nord. Ricard D. & Woessner R. (eds.) (2019): Les espaces ruraux en France, Éd. Atlande. Paris.

Rudolf F., Gobert J., Averbeck A. (2019): Adaptation to Climate Change as a Challenge for Sustainability Management in the Forestry and Timber Sector. Hamman P., Vuilleumier S. (eds). (2019): Sustainability Research in the Upper Rhine Region. Concepts and Case Studies. Strasbourg: Presses Université Strasbourg.

Sælensminde, I., Heiberg, E., & Aall, C. (2009). Hva betyr klimaendringer andre steder i verden for en norsk kommune? Et arbeidsverktøy for Fredrikstad kommune (In Norwegian. English translation of title: "What could climate change impacts taking place elsewhere in the world imply for a Norwegian municipality). Sogndal. Retrieved from https://www.vestforsk.no/sites/default/files/migrate_files/notat10-09-na-internasjonale-endringer.pdf

Sælensminde, I., Heiberg, E., Aall, C. (2009): Hva betyr klimaendringer andre steder i verden for en norsk kommune? Et arbeidsverktøy for Fredrikstad kommune (In Norwegian. English translation of title: "What could climate change impacts taking place elsewhere in the world imply for a Norwegian municipality? A working tool for Fredrikstad municipality"). Note 10/2009. Sogndal: Western Norway Research Institute. https://www.vestforsk.no/sites/default/files/migrate_files/notat10-09-na-internasjonale-endringer.pdf

Scott, D., Hall, M.C., Gössling, S. (2019): Global tourism vulnerability to climate change, Annals of Tourism Researchm Volume 77: 49-61

Scott, Daniel; Steiger, Robert; Dannevig, Halvor; Aall, Carlo (2019): Climate Change and the Future of the Norwegian Alpine Ski Industry, Current Issues in Tourism. https://doi.org/10.1080/13683500.2019.1608919

Scrieciu, S., Rezai, A., Mechler, R. (2013): On the economic foundations of green growth discourses: the case of climate change mitigation and macroeconomic dynamics in economic modeling. WENE, 2, pp. 251–268.

Selseng, T., Hønsi, T., & Aall, C. (2019). Kartlegging av barrierar og kunnskapsbehov om klimatilpassing i offentleg forvalting (In Norwegian. English translation of title: Mapping of barriers and need of knowledge about climate change adaptation in government). Retrieved from https://www.vestforsk.no/sites/default/files/2020-01/VF-notat 02_19_0.pdf

Stahl K., Weiler M., Kohn I., Freudiger D., Seibert J., Vis K., Gerlinger K. und Böhm M. (2016): Abflussanteile aus Schnee- und Gletscherschmelze im Rhein und seinen Zuflüssen vor dem Hintergrund des Klimawandels – Synthesebericht. KHR-Bericht I-25 (Projektleitung J. Belz), ISBN 978-90-70980-37-5.

Theys J., Fabiani J.-L.(1987): La société vulnerable. Paris, Editions des Presses de Sciences Po.

Tukker, A., Dietzenbacher, E. (2013): Global Multiregional Input-Output Frameworks: An Introduction and Outlook. Economic Systems Research, 25, pp. 1–19.

UNDRR (2019), Global Assessment Report on Disaster Risk Reduction, Geneva, Switzerland, United Nations Office for Disaster Risk Reduction (UNDRR).

Wei, D. and Chase, M. (2018). Climate and Supply Chain: The Business Case for Action. Report. BSR, San Francisco.

Wenz, L., Levermann, A. (2016): Enhanced economic connectivity to foster heat stress–related losses. Science Advances, 2, e1501026.

Wiedmann, T., Barrett, J. (2013): Policy-Relevant Applications of Environmentally Extended MRIO Databases—Experiences from the UK. Economic Systems Research, 25, pp. 143–156.

Wiedmann, T., Lenzen, M. (2018): Environmental and social footprints of international trade. Nature Geoscience, 11, pp. 314–321.

World Economic Forum. (2019). The global risks report 2019 (14th ed.). Geneva: World Economic Forum.

World Economic Forum. (2020). The global risks report 2020 (15th ed.). Geneva: World Economic Forum.

Zhao, H., Qu, S., Guo, S., Zhao, H., Liang, S., Xu, M. (2019): Virtual water scarcity risk to global trade under climate change. Journal of Cleaner Production, 230, pp. 1013–1026.

Zittoun P. (eds.) (2009): Des indicateurs pour gouverner: boussoles ou miroirs déformants. Éditions du PUCA. 196, Paris.

Final conclusions

The UNCHAIN project

The overall objective of the UNCHAIN project is to improve climate change risk assessment frameworks in order to improve the basis for decision-making and climate change adaptation action., by using the current version of the analytical tool “Impact Chains” as a point of reference. This tool was developed by EURAC Research for studies on climate vulnerability in the Alps and further developed for the national climate vulnerability assessment for Germany and the GIZ Vulnerability Sourcebook on climate vulnerability assessment in the context of international cooperation. The tool has also been adapted to the new IPCC Assessment Report (AR) 5 concept of climate risk and recommended for climate risk assessments in the context of Ecosystem Based Adaptation.

The UNCHAIN project will further develop ‘Impact Chains’ to support climate change adaptation capacity-building, by aiming at several methodological innovations of the current approach, of which this report covers the following innovations:

- To refine a structured method of co-production of knowledge and integrate this into impact modelling to better account for different views on desirable and equitable climate resilient futures
- To develop and test an applicable framework for analysing how societal change can affect local climate change vulnerabilities, how to conduct an integrated assessment of the combined effect of potential climate and societal changes, and how to better understand the socio-economic consequences involved in local climate change adaptation
- To explore the possibility of expanding the logic of impact change to include the transboundary effects of climate change

The goal of this report is to identify the specific challenges and knowledge gaps to be filled with respect to further developing the impact chain model. Thus, this report sums up the status of knowledge with respect to the three above mentioned innovative aspects of climate change risk assessments and starts off summing up an international knowledge review on the specific application of the Impact Chain tool.

The current application of the Impact Chain tool

Results from UNCHAIN can contribute to further improve the existing IC approach. Key elements are:

- a better integration of quantitative, semi-quantitative, qualitative and narrative approaches
- to consider and compensate the potential bias of the participatory elements within the assessment
- to include future vulnerability conditions based on socio-economic scenarios to better depict future critical conditions
- to address uncertainties and confidence levels for each step in the assessment
- to integrate knowledge from other approaches already existing in literature on the normalization and aggregation phases and the definition of critical thresholds

Particularly for more in-depth and scientific assessments it would be very interesting to forward the IC approach from a 'linear' representation of risk components towards more system dynamics-oriented models.

After considering the results from the systematic literature review and the experiences made in the field, it becomes evident that the refinement of the approach should take place from two sides. One is the design of participatory workshops to be as fruitful as possible, and the other is the improvement of data analysis, i.e. methods and models. Superordinate to these two points, one should always consider how best to communicate concepts, objectives, possibilities, limitations and results to stakeholders and end users. The clearer these points are communicated, the more likely it is that the results of a risk assessment will be regarded as legitimate by decision makers and implemented in the form of adaptation measures or adjusted management practices.

When considering modelling future risk in general, the well know problems of deep uncertainty about future climatic and socio-economic conditions, as well as the lack of data – even of present conditions – were identified as the major bottlenecks of recent risk assessments. When looking at the development of impact chains, the difficulty of identifying all relevant system elements and their interrelations plays a central critical role. Even though stakeholder involvement is immeasurable, it is intrinsic to human nature, that they will bring in selective perspectives, may lack better knowledge and experience, and/or are biased in some way. This should be considered in the subsequent analysis. Furthermore, methodical steps related to the data analysis need to be redesigned, e.g. aggregation.

A refined method of co-producing knowledge on climate change risks

Even though less than half of the identified studies describe whether and how the knowledge co-production process was evaluated, several lessons learned can be drawn regarding challenges and opportunities to knowledge co-production in relation to climate change risk assessments. These factors are also identified in related literature. Most cases in this review allude to the challenges of stakeholder representation, and scale and scope of projects in relation to decision-making contexts. Other challenges are differing perspectives and understandings of the problem definition, communication, and legitimacy of the climate information. Among the enabling factors, the role of knowledge brokers and intermediaries is highlighted as well as the use of interactive models and scenarios. Other factors relate to the stakeholder group composition, which clearly indicates the importance of investing resources in identifying and ensuring that all relevant stakeholders are represented and able to participate. Lastly, the opportunity to validate model results seemed to increase the legitimacy of the information and informing adaptation planning processes.

Moreover, we see few if any indications or clear results as regards to the role of knowledge co-production to inform adaptation decision-making. Hence, there is a clear gap and a need for further research illustrating important factors concerning how knowledge co-production processes can lead to actual adaptation action.

At the same time, it has been shown in other cases that – in relation to agenda setting – municipalities collaborating with academia has a positive impact with respect to that of facilitating local adaptation processes. We also know that stakeholders at different ends of the 'adaptation learning cycle' have different needs and capacities to engage in participatory processes, which also is likely to have an impact on the scope and outcomes of such a process. In this review we have not investigated these specific aspects. However, relating the challenges and opportunities to the differing case-specific contexts is something that possibly could bring further clarity to what works when and how, and is thus an interesting aspect to explore in future research and to consider specifically when conducting the UNCHAIN case studies.

Moreover, there is an ongoing debate and an acknowledged challenge in the wider transdisciplinary research community on how to evaluate the effectiveness of transdisciplinary research and how to link knowledge co-production processes with societal change. In addition to the often-cited criteria of credibility, saliency and legitimacy, many authors highlight the importance (and difficulties) of also considering external dynamics related to the process. For example, even though the process is assessed as being successful from a project perspective (or logic), there may be other (societal) and contextual factors that also needs to be taken into consideration in the evaluation.

To conclude, like other studies we see a lack of reflection and transparency as regards to stakeholder involvement in knowledge co-production and participatory processes. We also see the need to critically reflect on and be clear about stakeholder roles in the process as well as expected outcomes. This is key to enable better follow-up and comparison between cases which can lead to improvement and enhanced learning. Thus, in the Unchain case studies it will be important to carefully consider how these aspects can be captured throughout the different phases of the project. Moreover, in addition to the specified research question of how knowledge co-production can, in a systematic way best, be integrated in the current Impact Chain framework we also see that the research question specified for this knowledge review – the role of knowledge co-production in climate change risk assessments to better inform decision-making and adaptation action – is still of relevance for the project and should be considered when designing and conducting the case studies.

Analysing how societal change can affect local climate change vulnerabilities

In short, while the project tries to contribute to the development of a standardized analytical framework for gaining a better understanding of socioeconomic consequences involved in climate change adaptation, it connects different areas of research. To be able to do so, we must understand the current literature on socioeconomic scenarios and pathways and how they include climate change vulnerabilities, exposure and risks. The scenarios developed under the IPCC reports were scrutinized.

Three important factors have been identified to be crucial in the research for UNCHAIN:

- The element of scale. Climate change damages take place on a local or regional scale and do not respect statistical borders, such as federal states, municipalities or countries.
- The element of addressing risk and uncertainty.
- The relevance of different economic indicators for a science-based climate change adaptation strategy. Here, the fact that decision makers as well as the general public often relate much better to socio-economic indicators, such as GDP, production, costs, or well-being makes economic modelling an indispensable ingredient in the mix used for decision supporting information.

As an opportunity, the project can build upon existing work of its members. A good starting point seems to be the combination of dynamic IO models with the case study work on regionalization of economic and societal consequences.

Including the transboundary effects of climate change

Despite the initiation of sophisticated governance structures to manage adaptation at a sub-national, national and international levels of governance, the concept of transboundary climate change risk and the benefits of a scaled approach to adaptation are yet to be widely recognised. The assessments that have taken place have generated few tangible policy recommendations for how to adapt to transboundary climate change risks and even more limited responses and there are significant outstanding questions regarding who 'owns' such risks. This 'blind spot' of climate change adaptation is clearly weakest at the sub-national level of governance.

The review presented on the transboundary aspects of climate change risks has revealed some of the challenges to policy uptake that might be limiting factors:

- A series of factors that limit the capabilities of policymakers to address transboundary risks – including several knowledge gaps but also (and perhaps overlooked) skill and capacity gaps – despite several exploratory advances to drive conceptual clarity, design classification systems and invent robust methodologies in recent years;
- An arguably even more fundamental series of challenges in motivating policymakers to account for transboundary risks, given the lack of clarity about who is accountable for managing such risks and the lack of tailored arguments and incentives developed to motivate different stakeholder groups (which will be crucial given the inherent complexity of the topic, the 'hiding in plain sight' nature of transboundary risks and the political and normative factors incentivising a territorial view); there are perhaps opportunities to learn from the nascent demand for transboundary risk assessments from policymakers to date, to better understand who has initiated and utilised these and whether lessons can be learnt to encourage wider uptake;
- A promising array of policy windows and concrete opportunities to seed transboundary climate change risks into relevant policy agendas and organisational processes – revealing several opportunities to harness should capabilities become refined over time and incentive structures aligned. Still, these windows of opportunity most often present national and supra-national levels of government, leaving the sub-national level almost free of any initiatives pointing in the direction of how to address transboundary climate change risks at the lowest level of governance.

The UNCHAIN case studies will undoubtedly strengthen the evidence-base on transboundary climate change risk in identified countries and for relevant sectors, particularly if they advance the knowledge-base by addressing some of the identified gaps this review revealed and thus increase the capability of policymakers to act on their findings when synthesised with evidence from the wider field. The review also indicates that there are likely to be identifiable policy windows and processes within which findings can percolate and inform the design of policy responses – from the local to the national to the global level – which can be mapped and used to inform the timings and approach of concrete deliverables. But articulating and framing the findings in such a way so as to develop propositions that increase the motivation of identified and targeted policymakers to respond will also be important – exploring questions of governance and ownership, the political economy of risk management, the kinds of implementable policy recommendations that could effectively strengthen resilience to such risks and the existing national or regional policies that they could be directed towards. In such a way, the case studies could substantially advance the state of the debate on transboundary climate change risk.

Specifying research questions for the UNCHAIN project

Below we have listed the overarching objective and the research innovations of UNCHAIN as they were presented in the application and supplied them with several sub-research questions based on the findings from the extensive literature review presented in this report. The proposed set of sub-research questions will in the following works of UNCHAIN be linked to the cases, in order to secure that all research innovations are sufficiently addressed empirically. This will be done in the succeeding case study protocol.

- **Overarching objective: Improve climate change risk assessment frameworks aimed at informed decision-making and adaptation action**
    - How to identify the relevant **system elements** and their interrelations when doing impact chain analysis?
    - How to better **integrate** quantitative, semi-quantitative, qualitative and narrative approaches?
    - How to integrate in the impact chain framework knowledge from **other approaches** already existing in literature on the normalization and aggregation phases and the definition of critical thresholds?
    - How to forward the impact chain approach from a 'linear' representation of risk components towards more **system dynamics-oriented models**?
- <u>**Research innovation 1:**</u> **To cover also the possible need for long-term and large-scale efforts of 'societal transformation'**
    - How to link knowledge co-production processes with societal change, and how to evaluate the success of doing so?
- <u>**Research innovation 2:**</u> **To refine a structured method of co-production of knowledge and integrate this into impact modelling**
    - How to design of **participatory workshops** to be as fruitful as possible?
    - How to **critically reflect** on and be clear about **stakeholder roles** in the process as well as expected outcomes when doing impact chain analysis, and how to consider and compensate the **potential bias** of the participatory elements within the impact chain assessment?
    - How to increase the **level of reflection** and **transparency** as regards to stakeholder involvement in knowledge co-production and participatory processes?
    - How to best **communicate** concepts, objectives, possibilities, limitations and results to stakeholders and end users?
    - How can knowledge co-production in climate change risk assessments **better inform** decision-making and adaptation action?
    - What are the **challenges** to knowledge co-production in relation to climate change risk assessments, such as stakeholder representation, scale and scope of projects in relation to decision-making contexts, differing perspectives and understandings of the problem definition, communication, and legitimacy of the climate information?

  - What are the **promotors** of knowledge co-production in relation to climate change risk assessments, such as the role of knowledge brokers and intermediaries, the use of interactive models and scenarios, the stakeholder group composition, and the validation of model and the extant that this will increase the legitimacy of the information that goes into the adaptation planning processes?
  - What are the **critical factors** concerning how knowledge co-production processes can lead to changes in actual adaptation action, such as collaboration between public bodies and academia, and take into consideration that stakeholders at different ends of the 'adaptation learning cycle' have different needs and capacities to engage in participatory processes?
- **<u>Research innovation 3</u>: To develop and test an applicable framework for analysing how societal change can affect local climate change vulnerabilities**
  - How to include future vulnerability conditions based on **socio-economic scenarios** to better depict future critical conditions?
  - How to gain a better understanding of **socioeconomic consequences** involved in climate change adaptation?
  - How to **combine** the **differences in scale** between where statistical **data** is produced (within administrative borders at national, county or municipal levels) and where the **impacts** of climate change manifests itself (mostly independent of administrative borders)?
  - What are the most relevant **economic indica**tors to include in impact chain assessments?
- **<u>Research innovation 4</u>: To develop and test a standardized analytical framework for addressing uncertainties involved in local decision-making on climate change adaptation.**
  - How to better address **uncertainties** and **confidence levels** for each step in the impact chain assessment?
  - How to **overcome the problems of deep uncertainty** about future climatic and socio-economic conditions, as well as the lack of data – even of present conditions – when doing risk assessments?
  - How to address **uncertainties** related to the **socioeconomic aspects** involved in impact chain assessments?
- **<u>Research innovation 5</u>: To include the trans-national impacts of climate change and to link mitigation and adaptation in climate risk and vulnerability assessments**
  - What are the most important **transboundary climate change risk** in the involved countries?
  - How can **different levels of** governance identify and then adapt to transboundary climate change risks?
  - Who (private/public actors, at different levels and within different sectors) are **most accountable** for managing different sub-categories of transboundary climate change risks?
  - What are the most important factors that **limit** the capabilities of policymakers to address transboundary climate change risks?
  - How to **articulate** and **frame** transboundary climate change risks so it will increase the motivation of identified and targeted policymakers to respond to such risks?

Appendix

Appendix to chapter on the current application of the Impact Chain framework

Terms used in the search strings

Concept 1: related to risk assessment	Concept 2: related to climate change	Concept 3: Related to impact chains
Vulnerability assess*	Climat* change	Impact chain*
Risk assess*	Climat* risk	Causal chain*
Impact assess*		Causal loop diagram*
Adaptation assess*		Functional chain*
Needs assess*		Chain of effects
Indicator-based		Deterministic graph*
Bottom-up		Chain of impact*
Co-creation		System map
Co-production		Interdependencies
Disaster risk		Cascading effects
Critical infrastructure		Directed graph
		Network analysis

Inclusion Criteria

Inclusion criteria	Exclusion criteria
Risk/Vulnerability Assessment/Adaptation strategies	Not related to climate change
Impact Chains/CLD's used/system maps/network diagrams etc.	Conceptual articles (concepts, theories, frameworks)
In the climate change context	
Cross-sectoral assessment or single sectors	
Studies must be in English	

Coding scheme

Inclusion criteria (see Table 1) and additional codes		Code
Objectives and progress	Objective/Key research question/aim of the article	Descriptive text
	Progress made	Descriptive text
Modeling approach	Model type (IC, CLD, Bayesian, etc.)	Descriptive text (e.g. Impact Chains for Risk-based Vulnerability assessment, etc.)
	Model approach (participatory, literature, statistical, etc.)	Descriptive text (e.g. Stakeholder experience, expert judgements, existing models, etc.)
	Qualitative or quantitative model	Qualitative, quantitative, Semi-quantitative
	Validation approach	Descriptive text (e.g. Sensitivity analysis)
	Handling of uncertainty) (Yes-No; If yes – how?)	Descriptive text (e.g. scenario based)
Study subject	Country/Region/Sub-national	Country and/or region/sub-national area
	Sector(s)	Descriptive text
	Climate change risk(s)/hazard(s)	Descriptive text
	Governance level(s)	E.g. local, regional, national or continental
	Risk/Vulnerability definition	E.g. IPCC AR4/AR5
Challenges/Opportunities identified	Knowledge gaps/Challenges and barriers (on impact chains)	Descriptive text (e.g. data availability, stakeholder bias, identification of system elements, etc.)
	Suggestions/opportunities for improvement	Descriptive text (e.g. more stakeholder involvement, more appropriate model, etc.)

Summary table 'Lessons learned from CRVA'

Key features	Lessons learned using CRVA
Objective and outcome	- It provides information and indication on causes and magnitudes of specific climate impacts and risk, for a region, sectors and/or group of people - It includes and compare current and future climate risks and their changes - is an assessment and not a completely analytical and objective process - It prepares the ground for (and do not replace) a plan on adaptation measures - Participatory processes should be considered an objective and a valuable outcome, a capacity building activity for planning adaptation measures - vulnerability/risk maps and their main factors are the most important outputs
Relevant stakeholders	- National environmental ministries and agencies, line ministries and agencies, national statistical offices, national meteorological services, national Universities and private sector - Data and information provider should also be included in the assessment process
Time needed	- From a minimum of eight months for a very focused study (e.g. sub-national level, small number of spatial units, only one to two sectors) to at least one year for a national scale assessment - Two major bottlenecks: stakeholder integration is a time-consuming process, and difficulties on data access and collection
Relevant aspects to consider	- Factors and indicators should be defined as precise as possible answering the question "what leads to the risk?" (e.g. for heat impacts on health, a good hazard factor is not "temperature" but "heatwaves") - Cascading effects should be considered by defining "intermediate impacts" (e.g. a flood is an intermediate impact of heavy rain events, but acts as a hazard) - Social vulnerability can often be defined as the lack of adaptation (e.g. "missing early warning system")
Data and information	- Exploratory data assessments are often needed to understand data ownership and willingness to share it - Climate and emissions scenarios must be defined and considered within the assessment - Assumptions on future socio-economic projections or development should be included to better characterize vulnerability and exposure factors (e.g. population) - Qualitative approaches should be considered as an alternative and complementary way to get information (see Table 1)
Data aggregation	- Aggregation makes only sense if a relevant set of indicators can be quantified - Consistent indicators quantification and normalization is often a bottleneck in the assessment - A min-max indicators normalization is not recommended, since the comparability of different indicators after such normalization can be questioned. Alternatively, indicators can be normalizing with the help of a threshold for a "critical" value as the upper limit and an "optimal" threshold for the lower limit of the normalization - Although a simple (weighted) arithmetic aggregation is transparent, often does not reflect the fact that single risk components cannot compensate each other. Instead, a matrix approach might be more efficient - If many factors cannot be quantified nor aggregated, narrative conclusions can better support CRVA assessment aimed at identifying adaptation measures rather than compare different regions/sub-regions.

Appendix to chapter on co-production of knowledge

Concepts for the search and related synonyms

Concept 1: related to knowledge co-production	Concept 2: related to risk assessment or appraisal
Knowledge co$produc* *Knowledge co-production*	Risk* *Risk/risks*
Co$produc* of knowledge *Co-production of knowledge*	Vulnerabl* *Vulernable*
Joint* knowledge produc* *Joint knowledge production/product*	Impact* *Impact/impacts*
Science$policy interface	Adaptat* *Adaptation/adaptive*
Participat* action research *Participatory action research*	Impact* *Impact/impacts*
Stakeholder engage* *Stakeholder engagement*	Resilience
Stakeholder integrat* *Stakeholder integration*	*Multi$sector*
Stakeholder participat* *Stakeholder participation*	*Multi$risk*
Science$stakeholder process* *Science-stakeholder process/processes*	Hazard* Hazard/hazards/hazardous
Stakeholder interact* *Stakeholder interaction/interactions/interactive*	
Science$practice interact* *Science-practicinteraction/interactions/interactive*	
Collaborat* process* *Collaboration/collaborative process/processes*	
User interface	
Co$design	
Co$creat* *Co-creative/co-creation*	
Co$explorat* *Co-explorative/exploration*	
Science$practice interface	
Stakeholder involve* *Stakeholder involvement/involved/involve/involves*	
Transdisciplin* *Transdisciplinary/Transdisciplinarity*	
Participat* approach* *Participate/participatory/participation approach/approaches*	

Coding form of inclusion criteria and additional codes for analysis of full texts.

Inclusion criteria and additional codes		Code
Actors	Type of actor	Descriptive text of stakeholders involved (e.g. local decision-makers, planners, local experts etc.)
Intervention	Intervention (short description)	Descriptive text (e.g. climate change risk assessment, etc.)
	Aim of intervention	Descriptive text (e.g. evaluate climate change risks, etc.)
Knowledge co-production	Specific knowledge co-production approach	Descriptive text (e.g. participatory action research, participatory bottom-up approach, etc.)
	Role of stakeholders in assessment	Descriptive text (e.g. problem framing, etc.)
	Methods used to involve stakeholders	Descriptive text (e.g. workshops, etc.)
Study subject	Country	List of countries within the OECD
	Sector(s)	Descriptive text

	Climate change risk(s)	Descriptive text
	Governance level(s)	E.g. local, regional, national or continental
Outcome measures	Evaluation	Process; Outcome; Both; No evaluation
	Evaluation method	Descriptive text (e.g. qualitative or quantitative)
	Results of evaluation	Descriptive text
	Challenges and barriers to knowledge co-production	Descriptive text
	Opportunities/enabling factors to knowledge co-production	Descriptive text

Appendix for chapter on societal change and socio-economic models

SSP 1 – Sustainability (“Taking the Green Road”)

SSP 1 describes a development towards more sustainability, which is gradually being achieved and will change the world fundamentally. It marks a rejection of a resource-intensive way of life in society, which is exemplified by industrialized countries and increasingly adopted by emerging economies.

Table A *Characterization of SSP 1 (based on O’Neill et al. 2017, Bauer et al. 2017)*

Factor	Characteristics of the narrative
Population	High expenditure on education and health care accelerates demographic change.
Economy	The importance of economic growth is gradually shifting to the well-being of the population, which is becoming the focus of interest. Nevertheless, GDP can grow strongly, especially in developing and emerging countries.
Politics	Increasingly effective and consistent cooperation between local, national and international institutions, private companies and the population ensures better management of global public goods and reduces inequalities between and within states.
Technology	Technologies are being developed with a particular focus on environmental compatibility, which also increases interest in renewable energy.
Environment	Environmental conditions are improving due to high investment in new technologies and changes in tax incentives, resulting in higher efficiency and reduced consumption of energy and resources.
Resources and energy	Resource and energy intensity is declining as a result of more sustainable consumption patterns, which are being exemplified in industrialised countries, and a decoupling of economic performance and energy use. Only renewable energies (except biomass) are socially accepted energy sources.

This change of direction in policy results from social, cultural and economic consequences of environmental damage and inequality, which can be increasingly proven and are becoming more and more evident in the public awareness (O'Neill et al. 2017). An ambitious climate mitigation policy fits well into this setting but must nevertheless be implemented comprehensively on a global scale. Adaptation capacity is also high due to improvements in the prosperity of the population, which allows enough spending on adaptation measures, and the establishment of stable institutions.

SSP 2 – Middle of the Road

SSP 2 envisages a similar development in the economic, social and technological dimensions as in the past. This does not mean that recent trends are simply extrapolated into the future, but rather that the pathway is consistent with the observed structures of the past decade, reaching neither the lower nor the upper limit of possible outcomes (O'Neill et al. 2017). SSP 2 thus describes a business-as-usual development in which climate protection is pursued to a limited extent. These efforts are far from being enough to achieve the climate protection goals of the Paris Agreement, for example. The developments characterising SSP 2 pose medium socioeconomic challenges to climate mitigation and adaptation, which, however, differ significantly between and within countries.

***Table B** Characterization of SSP 2 (based on O'Neill et al. 2017)*

Factor	Characteristics of the narrative
Population	Global population growth is moderate and will decline in the second half of the 21st century. Investment in education is too low to reduce fertility rates in developing countries, so a slowdown in population growth there cannot be achieved.
Economy	The economic structures are the same as in the past.
Politics	Most economies are politically stable, but they develop differently and incomes grow asymmetrically.
Technology	Progress in technology continues, but without any ground-breaking developments.
Environment	Although energy and resource intensity is declining, especially in industrialized countries, environmental pollution continues.
Resources and energy	Fossil resources continue to be used (possibly using new extraction methods).

SSP 3 – Regional Rivalry ("A Rocky Road")

SSP 3 is characterized by a dominant protectionism driven by concerns about competitiveness and security and by spatial conflicts. This narrative is thus in contrast to the globalization trend of recent decades, which is possible under the assumption that certain events can invert current developments (O'Neill et al. 2017).

***Table C** Characterization of SSP 3 (based on O'Neill et al. 2017, Bauer et al. 2017)*

Factor	Characteristics of the narrative
Population	Population growth is low in industrialized countries and high in developing countries.
Economy	Economic output and also world trade are growing slowly.
Politics	As a result of a resurgence of nationalism, politics is increasingly oriented towards national and regional interests. The number of authoritarian forms of government is increasing, inequalities remain or grow.
Technology	Technological progress is slowing down due to lower investment.
Environment	The limited number and low effectiveness of global organizations and low priority given to environmental protection lead to high environmental damage.
Resources and energy	Due to the political situation, trade barriers are high, especially for the energy and agricultural sectors. Consumption patterns generate a high demand for resources. Economic performance and energy use are strongly linked.

Both mitigation and adaptation pose high socioeconomic challenges in this SSP. The former is caused, firstly, by the increasing resource intensity and the resulting high dependence on fossil fuels. In addition, slow technological, social inequality (especially between countries) and low international cooperation add to the burden, which, in combination with slow income growth, also increase the adaptation challenges.

SSP 4 – Inequality ("A Road Divided")

Inequalities both within and between countries characterize SSP 4. The population is divided into, on the one hand, a globally interconnected social class that contributes to the knowledge and capital-intensive global economy. On the other hand, there are fragmented population groups that work in labour-intensive and less technology-oriented economic sectors and have to get by with a low level of education and income. Various factors can contribute to such a development: On the one hand, technological progress has an asymmetrical impact on employment, which particularly threatens jobs requiring only low levels of qualification. Also, widely differing levels of investment in education increase unequal opportunities in the lab our market. Moreover, it is assumed for this narrative that less wealthy sections of the population have limited political influence and their chances of receiving credit are restricted (O'Neill et al. 2017).

Table D *Characterization of SSP 4 (based on O'Neill et al. 2017)*

Factor	Characteristics of the narrative
Population	Solidarity is loosening and conflicts and unrest are increasingly spreading. Population growth is low in industrialized countries and relatively high in industrialized and emerging countries. Development expenditure, e.g. on health care and education, is unequally distributed, generally medium in industrialised countries and low in developing countries.
Economy	While economic growth is moderate in industrialized and emerging countries, developing countries fall behind.
Politics	Power is concentrated in a small upper class of politicians and economists.
Technology	The technological progress is only strong in the highly technical economies and sectors.
Environment	Environmental policy in the industrialized and emerging countries is concentrated in individual areas, and vulnerable regions as well as global problems are hardly considered.
Resources and energy	In order to balance out price fluctuations for fossil fuels, energy companies invest in both CO2-intensive and low-carbon energy sources.

Due to some efforts to develop low-carbon technologies and the rapid response capability of international political and economic institutions, the socioeconomic climate mitigation opportunities are high. Adaptation requirements, on the other hand, are high for the majority of the population in developing countries, but adaptation capacities are low, as their access to institutions that could help them overcome economic and environmental problems is severely limited.

SSP 5 – Fossil-fuelled development ("Taking the highway")

SSP 5 is characterized by a basic economic liberal conviction that trusts in the effectiveness of competitive markets and innovations and supports a high level of participation by society. The central assumption for this is the acceleration of globalisation and technical progress (O'Neill et al. 2017).

Table E *Characterization of SSP 5 (ed on O'Neill et al. 2017, Bauer et al. 2017)*

Factor	Characteristics of the narrative
Population	High levels of investment in health care and education cause fertility rates in developing countries to fall, while in industrialized countries they rise to or even above the reproduction rate due to the positive economic outlook. Global population figures reach their maximum in the 21st century.
Economy	The global economy is growing rapidly, mainly due to developments in industrialized and emerging countries. Market structures maintain competition and remove barriers to participation by disadvantaged population groups.
Politics	Politicians enjoy a high degree of confidence in their ability to deal with social and environmental problems. The liberalization of labour markets increases international mobility and reduces income inequalities.
Technology	Rapid technological development and exchange are achieved with the use of fossil fuels.
Environment	Local environmental problems can be effectively addressed through technological solutions. At the global level, however, there is little effort, as the avoidance of environmental pollution is seen as a trade-off to economic growth.
Resources and energy	A resource- and energy-intensive lifestyle is spreading worldwide, which is countered by the depletion of fossil resources. The use of fossil fuels is widely accepted by society, while renewable energies are not widely recognized.

As a result of the high use of fossil fuels and the lack of environmental concerns at the global level, the socioeconomic challenges for climate mitigations are high, because climate protection is a priority and GHG emissions will be very high even compared to the other SSP baselines. On the other hand, there is a high capacity to adapt due to the high development goals, robust economic growth and highly technological infrastructure. It is assumed that with enough financial resources, existing technology, well-developed infrastructure worldwide and stable institutions, a high degree of adaptation to climate change can be achieved quickly, because this is politically intended and, given the rapid pace of climate change, necessary.