Transboundary climate risks – a literature review

Working paper

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Contents

1 Introduction

With the advance of climate change and global trade being diversified and intensified further, the issue of physical climate impacts on supply chains has become increasingly relevant (McMichael 2013; Wenz and Levermann 2016). The importance of this topic has been recognized on different policy levels (e.g. EU: EC 2013: 4; Germany: Bundesregierung 2011 and 2015; federal states (Bremen): SUBV 2017). However, the past political debates show that there are large knowledge gaps on the extent and relevant of such transboundary climate impacts with respect to Germany (Deutscher Bundestag 2016; debate triggered by Wenz and Leverman 2016) and that the overall research on this topic is at a relatively immature stage (Benzie et al. 2017: 15).

This working paper presents the results of a review of publications on the topic of transboundary climate risk with a focus on impacts on trade flows and supply chains. The paper was written as part of the project "CLIC" funded by the German Federal Ministry of Education and Research. The paper was prepared in 2019 and then updated in 2022, against the backdrop of the impacts of the COVID-19 pandemic on global supply chains.

The paper is structured as follows: after this introduction, chapter 2 briefly provides an overview on the different scientific disciplines that tackle the topic as well as the terminologies employed. Chapter 3 presents the results of the reviews as well as discussion of them. The paper concludes by highlighting the relevant dimensions and factors for assessing transboundary climate risks (chapter 4).

2 Perspectives and terminology

Studies in the field of risk management including a global perspective are to be found as early as the 2000's, when Linnerooth-Bayer et al. (2001) worked with the concept of transboundary risks to study risks that occur in one place but also have impacts in other places across different types of borders, while also considering environmental, political and social implications. Tait and Bruce (2001) discussed the concept in more specific terms, namely in the area of food trade, thus specifically elaborating on the term "traded risks", referred to those risks that cross-national boundaries as a result of commercial transactions (Tate & Bruce, 2001, pp. 100).

As for the specific topic of international or cross-border impacts of climate change[1], publications come from different types of sources. First, academic journals mostly provide case-study analyses, such as publications from Adger et al. (2009); Liu et al. (2013); Oh and Reuveny (2010), setting the ground for conceptual and methodological discussions. Then, international agencies produce reports on a regular basis at a global or regional level, elaborating on multiple topics related to climate change, the Intergovernmental Panel on Climate Change (IPCC) and the European Environmental Agency (EEA) being two important references. Also, national governments have called for input on national risks and opportunities evaluations, usually answered by private consultants that publish the evaluations' results as well as policy recommendations at a national level. Here, for example, the UK counts on three different reports (the Foresight, PwC, and the UK Climate Change Risk Assessment). Finally, research institutes such as the Stockholm Environment Institute develop research lines within the topic as well as non-governmental organisations such as Oxfam that engage with private stakeholders to develop solutions.

Within all types of sources, a wide variety of terms is used to describe the phenomena of climate impacts on trade activities which can be taken as a sign for relative novel nature of research in this area as well as the multiple approaches it is subject to. Benzie et al. (2017) explored 17 terms used for describing the same or similar phenomena and analysed them according to the advantages and disadvantages each of them presents for the general conceptual delimitation of the phenomena.

For instance, some terms were deemed to be too vague or, on the contrary, too specific. At the same time, there are counter-intuitive terms as well as others that are highly linked to a technical language, thus presenting a restrictive use. The classification also shows that each term is closely related to its academic field. In this sense, and elaborating on the presented The **policy perspective** is based on governance demands and challenges and adopts terms such as "transnational climate impact" or "international dimensions" of climate change.

International Dimensions can be defined as: "risks and opportunities for the UK from the observed and projected impacts of climate change globally." (Challinor et al. 2016, p. 7)

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[1] We refer to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change for a definition of "Impacts": "Effects on natural and human systems. In this report, the term impacts is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change (…)". Further definitions on the realm of climate can be found on the Glossary of the report's Annex II. IPCC, 2014: Annex II: Glossary [Mach, K.J., S. Planton and C. von Stechow (eds.)]. In: 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, pp. 117-130.

The **geographical perspective** focuses on the location of the effects in relation to its origins, therefore expressing the phenomena in terms of "transboundary", "cross-border", "long distance" or "telecoupled" impacts of extreme weather events and climatic changes.

Transboundary impact: *"Transboundary* impacts are transmitted over borders between neighboring countries" (Benzie et al. 2016, p. 8)

Transboundary risk: "transboundary risks, those generated under one regulatory jurisdiction with significant actual or anticipated impacts in another jurisdiction, regionally or globally" (Tait and Bruce 2001, p. 99)

Cross-border impact: "describe impacts that operate across jurisdictional boundaries, without necessarily implying a direct crossing from one neighbor to another." (Benzie et al. 2017, p. 15)

The **sequential perspective** highlights the level of connectedness of impact chains, hence "indirect", "cascading risks" or "first, second and third order" climate impacts are appropriate terms in this case:

Indirect impact: "impacts that are observed or expected in one place, but are brought about by climate change or extreme events somewhere else" (Benzie et al. 2013, p. 1)

(Systemic) Cascading risks: "Systemic climate risks, which result from the potential for cascading impacts through inter-related systems, pose particular challenges to risk assessment, especially when risks are transmitted across sectors and international boundaries." (Challinor et al. 2018, p. 1) "There is widespread recognition of the potential for cascading failures in trade, financial, infrastructure, health and environmental systems, and the role of climate change in initiating cascades." (Challinor et al. 2018, p. 19)

In this working paper, we will mostly be using the terms transboundary climate risks or cross-border climate risks.

3 Literature review

The goal of the literature review at hand is to capture the current state of both the academic and the more policy-oriented discussions on the assessment and relevance of trade-related cross-border climate risks. More specifically the review aims at:

- Identifying the past extreme weather events that have been at the core of the discussion;
- Identifying and describing key methodologies for assessing cross-border climate risks on a national level;
- Reflecting the current methodologies and their use of different data sources and
- Identifying research gaps

In the context of the CLIC project, this review also serves the purpose to prepare related analyses in Germany that build on the current state of knowledge and contribute to closing research gaps.

3.1 Method

The usefulness of the key-terms search's results was very limited for the purpose of identifying key publications to build on the literature review for CLIC's very specific topic. On the one hand, this was due to the above-mentioned lack of a consistent, shared terminology. On the other hand, the diversity of perspectives also led to non-academic sources. Sometimes only a section of larger reports touched upon the topic making it difficult to identify them only through key-word search.

Therefore, a snowball sampling was chosen over a key-terms search in order to create a map of publications based on citation patterns, providing a broader picture on the given topic and the relationships to other fields (Lecy et al. 2012).

The snowball sampling starts with the identification of seed articles, a start set of papers covering a variety of sources (Lecy et al. 2012; Wohlin 2014). A good start set should include papers from different communities or sources, from a variety of authors, publishers and publication years (Wohlin 2014). In the case of the CLIC project, the general tendency of including recent publications (Lecy et al. 2012) was intentional, given that the specific delimitation of the topic and combination of fields for its development is also rather recent.

Once the start set is determined, the procedure follows with a backward sampling. For this step, the reference list of each paper in the start set is observed, excluding papers that do not fulfil certain criteria, for example, because they do not refer to the studied topic or because they fall out of the preferred time frame. For this first assessment, the title, publisher and authors are main indicators of relevance (Wohlin 2014). Then, if a referenced paper is still relevant, the context of citation is evaluated in order to check the connection to the topic. Another way that has proven to be more direct is to note references right away while reading a highly relevant passage in the paper. Finally, if the referenced paper is estimated as relevant, then the abstract is read and a general scan reading is done. If relevance is confirmed, the paper is included in the first iteration of the snowball sampling.

A forward sampling is also carried with start set papers. This time, papers citing a start set paper are identified using search engines like Google Scholar. Here, all papers citing are evaluated and screened using the same procedure as for the backward sampling.

As for the CLIC project, backward sampling has proven to provide more papers for the following iterations, as the ones suggested by the forward sampling presented a tendency to widen the research scope beyond the delimited topic.

After completing the first iteration, the same backward and forward sampling are resumed until no new relevant papers are found, or until covering the main topics of the research question.

3.2 Results

Papers and reports included in the sampling were analysed through content analysis using categories in Citavi. The first readings of the start set papers led the development of the categories, and they were checked and completed with initial readings of the first iteration, according to CLIC's projects aims.

A content analysis followed for all papers of the snowball sampling, namely 47 titles were analysed through eight categories and four sub-categories.

The most relevant categories focused on the methods for assessing transnational climate impacts, which include, for example, descriptions of indicators used for identifying possible pathways of climate impacts, economic modelling and case studies. Research gaps are also among the most relevant categories that provided insights on the challenges of quantifying indirect climate change impacts and the existing evidence gaps in the areas of trade, food supply and industry impacts. We also identified all actual and potential pathways of cross-border impacts, where we noticed that sources engaged more frequently with potential cross-border impacts, while referencing only a limited number of actual pathways. The following table illustrates the most frequent examples used for explaining cross-border climate change impacts, out of 47 screened papers, including academic articles, country and international reports.

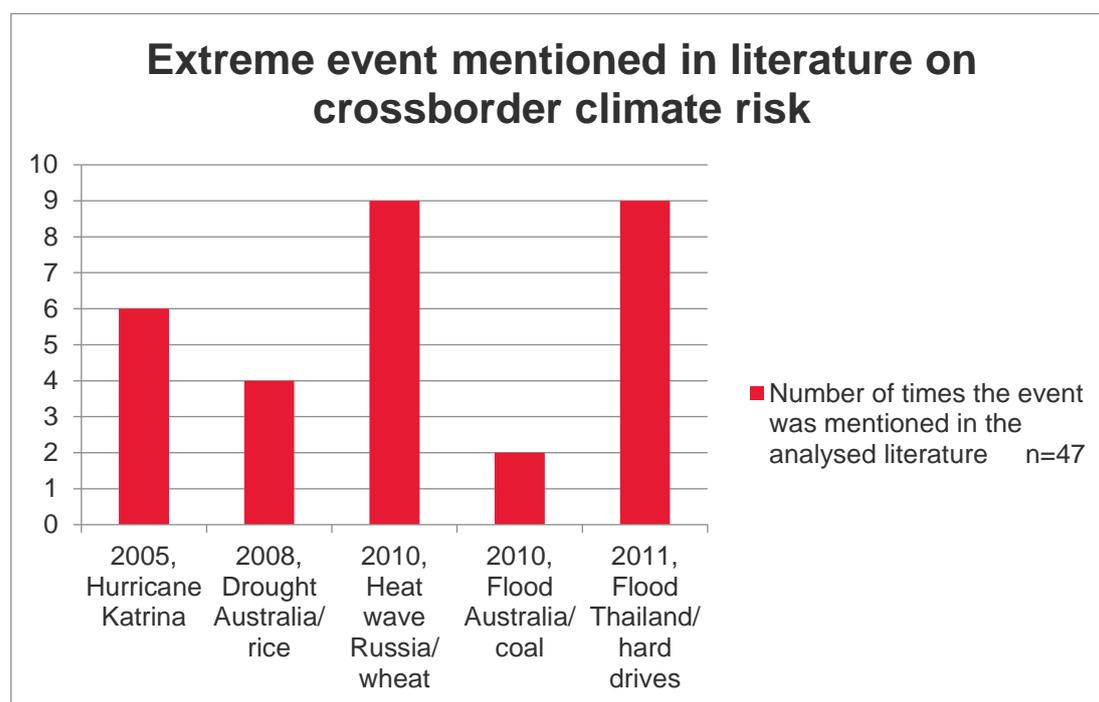## Extreme event mentioned in literature on crossborder climate risk

Figure 1: Events analysed most frequently in the literature (own illustration)

3.2.1   Overview on studies on the national level

Studies of cross-border climate risks that focus on one importing country are of particular relevance for this review, as one of the goals of CLIC is to conduct such an analysis for the country of Germany. In the following, approaches and insights from such country reports will be presented.

Looking at such publication, the reports on the UK and the Netherlands stand out among country reports on similar topics to CLIC (see table 1). First, these reports explicitly acknowledge and deal with the topic of cross-border impacts of climate change and climate events. Second, they also cover the area of trade quite thoroughly, while still considering other pathways. Finally, all of them have a strong focus on evaluating vulnerability risk and opportunities within different time frames in order to point out research gaps and to elaborate policy recommendations.

Table 1: National analyses touching on trade-related cross-border impacts

Year	Country	Title	Commissioned by
2011	UK	Foresight International Dimensions of Climate Change	Government Office for Science
2013	UK	International threats and opportunities of climate change for the UK	Department for Environment, Food and Rural Affairs
2015	Netherlands	Worldwide climate effects. Risks and opportunities for the Netherlands	PBL Netherlands Environmental Assessment
2017	UK	UK Climate Change Risk Assessment	Adaptation Sub-Committee on Climate Change
Older studies: Switzerland 2007 (Schwank et al.); studies in other languages: Finland 2015; more recent studies: USGRCP (2018): US 4th National Climate Assessment; on-going studies: Infras for Germany, SEI for Sweden.			

The report on "International threats and opportunities of climate change for the UK" focuses on five main themes: Business, trade and investment; Infrastructure (focus on energy); food; health and wellbeing; and foreign policy. The report's approach is based on identifying threats and opportunities; gaps and recommendations, as well as considering the time scope of 2020, 2050 and 2080. The analysis looks at the magnitude of impacts and level of confidence. Finally, the report presents case studies for each theme.

Methodologically, the approach in the report was as follows: Information was gathered based on expert opinion, with an Advisory Panel and a Stakeholder Workshop for defining themes and indicators, assessing threats and opportunities and discussing case studies. In order to evaluate international relations of the UK in respect to climate change, the report categorises countries according to their different linkages to the UK, such as trade, investment and cooperation, climate impacts and vulnerability. Here, the report is strongly based on the UK Climate Change Risk Assessment (CCRA), thus scoring threat and vulnerability following UK CCRA Report's main themes and magnitude of impacts, the IPCC 4th Report, along desk research, consultation with experts and stakeholders.

To evaluate vulnerability, the report composed an index by combining the Worldwide Governance Indicators (WGI), the Human Development Index (HDI) and the ND-GAIN Vulnerability Index, in equal weight. For trade and investments specifically, the report draws on indicators of imports, exports and assets abroad. For the case study on trade, concentration of exposure and magnitude of consequence and confidence are the dimensions for analysing supply availability of imports; whilst the case of food is analysed following the magnitude of food imports from each country by value.

The main findings related to trade show risk of damage of assets and investments abroad; increased price volatility and shortages; failure in transportation and distribution networks, including reduced access to import and export assets. These threats are categorised according to their magnitude in each time horizon, along a low and medium level of confidence.

The report also presents a categorisation of links to countries according to their vulnerability. Finally, threats are also accompanied by opportunities, which in short refer to a potential to export adaptation goods and services, reducing shipping costs from Arctic opening; and attractiveness of UK as an investment location.

The Netherlands Report focuses on risks and opportunities of climate change abroad. These are classified according to their likelihood and impact (using sources provided by the PBL Netherlands Environmental Assessment Agency). To this end, the report establishes ways in which the Netherlands is connected to other countries (with data based on Statistics Netherlands, UN Comtrade, OECD, Teleography, Dutch Ministry of Foreign Affairs), to then list climatic effects that may occur in these countries according to their vulnerability using the Notre Dame Global Adaptation Index ND-GAIN as source. The report is based on information derived from other publications and data sets in collaboration with the Meteorological Institute and the Institute of International Relations in the Netherlands.

The main results in the field of trade refer to risks in price hikes, along temporary shortages or interruption in supply chains, particularly soy supply vulnerability. Flooding risks are also identified. Still, the report expresses that the Netherlands will not suffer systemic nor macro-economic failures.

The UK Climate Change Risk Assessment 2017 identifies policy gaps and works with recent evidence based on peer-review scientific literature, grey literature and with direct engagement with individual companies and business representatives. An independent group of technical peer reviewers, government stakeholder and non-government reviewers reviewed the report and expert judgement from the Adaptation Sub-Committee also worked in the assessment of urgency.

In the chapter about international dimensions, food systems is the first topic. With respect to trade, the results show that an absolute availability of food is unlikely to be an issue for the UK. Still, increased food prices would disproportionately affect lower income households. In regards to business and supply chains and distribution networks, the key messages are the importance of adaptation and resilient transport infrastructure and ports, considering increases in extreme weather events and UK's reliance on overseas markets.

The 4th National Climate Assessment of the US, dedicates a chapter to the climate effects on U.S. international interests. It recognizes that climate change and climate extremes occurring outside the US can directly affect trade and economy. The report was produced by a team of more than 300 experts, supported by workshops, listening sessions, webinars, public comment periods and regional engagement workshops across the country. It was then reviewed by external experts and the general public. The vast majority of the report's sources are from peer-reviewed scientific literature (Lewis et al. 2018).

The German Environment Agency published preliminary results of the research project "ImpactCHAIN" (carried out by INFRAS) in November 2018. The research's aim is to analyse whether and to what extent Germany would be affected by climate change through foreign trade in the future. The working hypothesis states that climate-related impacts in countries that are important trading partners for Germany will bring additional risks and possibly also opportunities for the German economy. After identifying the most relevant impact chains, the project attempted to quantify and model selected impact chains to compare their relevance to impacts that are strictly within the national boundaries of Germany.

Based on literature research and expert assessments, the project team identified impact chains and assessed their relevance according to a combination of opportunities and risks.

Besides, the study also evaluates Germany's import and export trading partners. Among them and based on ND-GAIN, the study identified the most vulnerable ones to climate change. Even if most of Germany's trading partners are highly resilient, the report did identify twelve regions or countries that are particularly vulnerable.

The preliminary results indicate that the import sectors could entail risks through three main impact chains: a) buildings, production sites and storages located in climate vulnerable countries will be affected by storms, inundations and heat; b) agricultural productions can be massively affected by continuous heat periods, heavy rain events or storms; c) transport of goods will be mostly affected by impacts on shipping, but here the preliminary results also show some opportunities related to the extension of shipping seasons or the opening of new routes.

In the export sector, a) climatic changes will dampen the economic growth, and along that, the purchasing power and private consumption; b) the technology sector can benefit from growing markets not only for climate adaptation but also for climate-friendly products. Other impact chains for both import and export sectors are identified and described among the preliminary results, in various combinations of none, low, medium and high risks and opportunities.

3.2.2 Methodologies applied

The findings above show that desk research and literature review of peer-review journals and grey literature are common starting points of reports. Most country reports also count on advisory panels where experts from public and private sector including academia provide their opinion on prioritizing themes and suggesting indicators to measure climate impacts. The expert collaboration usually consists of multiple rounds and exchanges, as can be seen in the UK CCRA and even more diversified audiences for the case of the US 4th National Climate Assessment.

Country reports often use indices that can provide insights on the level of connectedness and dependency of countries around the world with the country in question. In some cases, indices were selected making use of external experts. The indices cover connectedness or dependencies through various channels such as food imports or development cooperation. Then, these indices are weighed and compared with other sets of indicators in the realm of climate change vulnerability and climate extremes locations.

Economic modelling is used to quantify risks, and it can focus on different components of weather and climate change such as increased temperatures or GHG emissions. As method, "modelling provides a means to capture greater numbers of interactions, the relative contribution from different components, and system complexity, within the constraints of its underlying assumptions to simplify reality. Integrated Assessment Models (IAMs) aim to combine, interpret and communicate knowledge across a range of disciplines and have been widely developed and used to identify impacts associated with climate change" (Challinor et al. 2018, p. 9). IAMs are one of the main analytical tools to assess and predict the macro-economic impacts of climate change. They capture and combine physical, natural and social dynamics of climate change and have been used on a variety of studies including the IPCC Report (Batten 2018, p. 12).

Further empirical research also draws on panel methodologies for identifying causes of cross-sectoral and cross-border effects of climate change in the economy. Thus, by selecting weather outcomes, their impacts on yield, labour, energy demand and other economic and social process can be traced and measured (Dell et al. 2014, p. 741).

3.3 Discussion of methodologies

The sources identified in the literature review employ a variety of methodologies for identifying and analysing transboundary climate risks. The main approaches are discussed in the following sections.

3.3.1   Expert consultations

Looking at reports on the national level described above, expert consultations are at the core of information gathering for assessing climate risks transmissions.

In the case of the UK Climate Change Risk Assessment 2017 this was done very transparently: the report's draft reviews were carried out systematically and the results – including expert and reviewers' comments – remain available for the public. The report presents a specific chapter to explain decision-making processes, where the iteration and the diversity of participants in the review processes give a sense of objectivity in the overall evaluation of information and identification of any possible gaps or errors. Further on, the same chapter presents some of the concepts used and that were key for the assessment and consistency of descriptions. Given the lack of common terminology and the multiplicity of uses of some concepts beyond the technical or environmental scope, we consider that this is an important step to be considered.

Another aspect when considering expert and stakeholder consultation consists on the selection of data sources, indices and construction of composite indices. In the case of the report "International threats and opportunities of climate change for the UK" (in the following: the PwC report"), the authors propose a new composite index resulting in an average from the combination of three indices. With these three indices, referring to governance (WGI), human development (HDI) and climate vulnerability (GAIN), the report seeks to achieve an overall evaluation of countries beyond biases that could emerge if only one index was used. Nevertheless, it remains unclear how the indices were selected and why it was decided to aggregate them with equal weights.

In both the UK CCRA and PwC report, the methodology was based on literature review and expert consultation. They also built on already existing reports and previous versions for assessing a scale of urgency and thematic scopes. Even if this facilitates a consistent comparison and evaluation of risks and opportunities, it could also reproduce research gaps and limit the scope of analysed phenomena.

A plurality of methodologies might be advantageous for assessing complex phenomena such as transboundary climate risk transmission. In that sense, "the combination of methods needs to be able to incorporate plausible, but often unknown, risks and transmission mechanisms alongside better characterised ones. This is important because indirect pathways can very often exert a much larger influence than direct pathways in complex systems, which can be highly non-linear in nature" (Challinor et al. 2018, p. 17). This combination of methods and approaches also considers the inclusion of expert judgements, which should be rigorously framed in order to avoid biases (Challinor et al., 2018, pp. 18).

Challinor et al. (2018) also recommend scenario-based approaches for studying parameters of future conditions, opportunities and threats in order to help with the designing of policy and planning strategies. In this case, scenarios can be developed through both qualitative and quantitative methodologies including expert judgement. Identifying analogues conditions in

space or time is still another recommendation for complementing qualitative approaches and identifying possible blind spots left by quantitative modelling.

The complex transmission of climate change goes beyond separate disciplines, that, even if already individually advancing in the study of cascading effects, still recognize the need of multi- and trans-disciplinary approaches for the study of interconnected systems (Challinor et al. 2018).

3.3.2   Case studies

A case study approach can contribute to depicting still insufficiently explored topics. In that sense, case studies can explore and evaluate relationships between phenomena that are not all evident, typically through "how" and "why" questions for analysing numerous context variables (Gray 2014). Hence, case studies may aim at expanding on existing knowledge while looking for explanations in a real-world-based case (Yin 2014).

Following Yin (2014), a case study has a twofold definition, which refers to both the scope of it, i.e. it investigates a phenomenon in depth and in its context; and the features of it, i.e. it has a large number of variables and sources, and it benefits from prior theoretical knowledge.

Typical concerns about case studies mainly refer to the possibilities of generalizing. Nevertheless, case studies do not pretend to be samples of a wider reality (Yin 2014) but to build on existing knowledge on a certain phenomenon while linking it to real cases and depicting explanations to that case. The contribution of case studies, therefore, refers to expanding theories and gaining an in-depth understanding of how they reflect on concrete cases, all while presenting evidence for further discussion.

Abe and Ye 2013 for example, make use of this methodology for exploring natural disasters risks within supply chains. By exploring a case in depth, the authors argue, the study can provide insights on multiple levels of risks such as direct and indirect impacts and on different entities/stages of a supply chain. In their study, authors recognize a gap in research with regards to the impacts of natural disasters on global supply chains, which even if not as frequent as other disruptions, are nevertheless very intense. Therefore, they propose to explore how natural disasters affect global supply chains based on the case of an earthquake in Japan and floods in Thailand that took place in the year 2011. Both cases were chosen because of the natural disasters' relevance in recent history and because of their role in supply chains, thus the events were the starting point for selecting the cases, following a relevant linkage to the topic. Thailand is a major supplier for the auto and electronic sectors and Japan is both supplier and end products producer, where manufacturing and chemical industries suffered the most.

In their article, the authors describe each case individually and cover different variables of the natural disaster's impact. While referring to the event and the context, they point out effects on supply chains (local and expanded disruptions in supply lines, declined production), finance (lack of complete or partial insurance, raise in insurance policies, increased or loss in market shares, price fluctuation of supplies), structures (local and expanded infrastructural damages; shortages in power supply), human capital and labour market, relocation of production sites, additional costs for companies (adaptation, insurance), and loss of confidence and questioning of investment destinations. The presentation of concrete outcomes such as volume of production loss, market shares, monetary loss, and countries/companies connections, illustrates each case.

The authors then synthetize the descriptions with a conceptual analysis presented as a flow diagram, where participants, contexts and connections are identified in a schematic way, thus beyond the particularity of cases.

Another entry point for selecting cases consists on addressing companies. For instance, Oxfam's research (Thorpe and Fennell 2012) worked with three companies engaged in climate change and sustainability. The companies rely on agricultural commodities coming from (among others) small-scale suppliers that have undergone difficulties because of unusual climatic conditions, in this case coffee in Colombia, cotton in Pakistan and sesame plantations in Nicaragua.

As the publication is focused on action and advocacy, the selection of cases, topics for the interviews and the analysis are also directed towards highlighting good practices and elaborating on recommendations. Contrary to how and why questions particular of case studies, in this research, questions aimed at gaining insights on actual practices and experiences of companies, while looking to identify concrete behaviours and information that could build on action recommendations for further companies.

To this end, the report presents each case study with a general overview of the agricultural and environmental challenges of each crop, which are based both on literature and on interviews they carried with representatives from each company. Then, cases present the company's commitment and briefly explain main sourcing and supply chain challenges and strategies.

This report describes commitment strategies from particular companies with suppliers in a context of climate vulnerability, hence presenting examples of concrete measures that could help improve resilience. Even if highly necessary, the report does not address empirically the connections between impacts and adaptation measures that companies put into action when suppliers suffered climatic challenges. In that sense, the case studies are meant as an overall evaluation rather than as a comparable analysis. Still, the results are valuable as they point towards the field of preventive action, sustainability and supply chain responsibility.

Lastly, yet another approach is possible by focusing on key supply chains. These may be relevant because of its monetary value or because of "strategic importance". For instance, the PwC report presents a case study on food, namely cereals. The report presents short-, medium- and long-term food supply chains projections based on a comparison of import dependency indices, a ranking of sourcing countries and its correlating weather vulnerability data and population projections.

This approach aims at presenting threats and opportunities in regards to a particular supply chain which is considered of strategic relevance and as more vulnerable than others, based on national trade data. Sources are mainly quantitative and the analysis and correlations remain based on expert opinion and limited to the selected variables and projections.

Overall, sources for all case studies may come from both quantitative and qualitative data. In the examples mentioned above, authors refer to quantitative data from international data sets, national statistics, and other institutions such as chambers of commerce or private companies. Data here refers to values in imports, in production and even quantified monetary losses. Qualitative data come from interviews with experts, surveys and descriptions from literature review.

The previous examples show the variety of uses given to case studies that, even if not all of them provide strictly theoretical applications, do provide access to more grounded information of what is hypothetically or generally known. In that sense, limiting the aims and scope of each

approach remains necessary in order to prove methodological consistency in all types of reports.

3.3.3   Existing indices

As previously noted, global indices of country's climate vulnerability and risk are often main sources of information for the literature reviewed. Indices differ among the results they provide and carry some caveats that should be considered. Mainly, these have to do with the fact that "no common reference metrics exist for assessing the main components of climate change risk. This is due to many factors such as the conceptual confusion around the key elements of vulnerability, adaptation and resilience due to different scientific communities that have tried to resolve it (Füssel, 2007; IPCC, 2014, Miola et al, 2015)" (Miola, n.d.).

In that sense, there is no agreement on the climate or weather events that should be considered as related to climate change risks. Also, no common definition is to be found in regards to climate risks and its components, nor for vulnerability: the approaches vary at least between risk-hazard or political economy-oriented (Miola, n.d.). What is more, global indices may ignore country's particularities which could mean "special cases" of vulnerability (Füssel, 2009).

Likewise, many indices work with national indicators based on institutional performance, although "no scientific evidence exists (or provided by the analysed indices) on a causal link between proposed indicators on institutional capacity and increased climate change risk." – however, a link between poverty and climate change can be recognized (Miola, n.d.).

One further weakness pointed out by Miola (n.d.) consists on the lack of transparency of the underlying values of each indicator, as in several cases they cannot be decomposed. For some indicators, lack of consistent data across countries can also contribute to a biased mapping of vulnerability and risk. Considering the example of weather events, data is often missing for the case of developing countries (Miola, n.d.). Mathematical methods and summation of indicators also usually assume that indicators are substitutable, whereas this is not necessarily empirically proved (Füssel, 2009).

Recommendations in the field of international development point out that political decisions and funding assignment should not rely solely on global indices comparisons but use them only as a preliminary assessment (GIZ, 2017).

The Transnational Climate Impact Index (TCI) from the Stockholm Environment Institute (SEI) offers a comparison between ND-GAIN and the TCI to illustrate differences in rankings when considering a particular focus and variables. Here, Europe is the most heavily represented region in regards to exposure, thus showing its high dependency on neighbours and global systems (Benzie et al., 2016). It is also possible to recognize for which pathways countries score rather low or high, hence making evident which pathways are vital when assessing transboundary impacts. Here, the TCI indicates that there are fewer correlations between high income countries or high human development and exposure – unlike what other indices show, therefore indicating that transnational climate impacts are much more complex and country specific (Benzie et al., 2016).

3.3.4   Addendum to the review

In 2022, three years after the initial literature review – that makes up the main body of this document – was concluded, we added the following paragraphs to account for two important

publication: one that focusses on adapting to transboundary climate impacts (Bednar-Friedl et al., 2022) and one that touches on learnings from the COVID-19 pandemic for dealing with transboundary climate impacts (Ringsmuth et al., 2022).

In their systematic literature review on academic and grey literature, Bednar-Friedl et al. (2022) investigated relevant stakeholders and knowledge transfers on the adaptation of both agricultural and industrial sectors to reduce transboundary climate risks. In doing so, they aimed to answer three research questions regarding

- the relevant transboundary climate risks for agricultural products and industry supply chains,

- the potential adaptation options (and their conflicts) to these, and

- the key actors to manage transboundary climate risks as well as the major sites where action takes place.

After defining relevant climate hazards, their risks to trade, categorizing adaptation options and identifying relevant actors and locations where adaptation may be necessary, the identified categories were used in a query on the knowledge platform SCOPUS using different operators. After two elimination steps, 56 peer-reviewed academic papers and 24 pieces of grey literature were identified as suitable for the purposes of the literature review. At this stage, it was already obvious that the majority of papers deals with the effects of transboundary climate risks on agriculture and food trade which may be due to the direct impacts of climate and weather on agriculture and thus a higher awareness for the need to act and adapt (Bednar-Friedl et al. 2022).

In line with the findings presented in chapter 2 above, Bednar-Friedl et al. (2022) found a high diversity of terms relating to transboundary climate risks. Regarding the first research question, it became apparent that droughts, increasing average temperatures and increasing heat extremes are mentioned as the most relevant climate related risks for the agricultural sector in the scientific papers. In the grey literature however, precipitation-related hazards such as flooding and extreme rain events are mentioned almost as often as droughts which are still the most mentioned hazard. The authors suppose that this bias is due to "clearer climate signals in temperature-based indicators" (ibid.). These hazards result most frequently in food insecurity in developing countries and food supply shocks and unaffordability in developed countries due to yield losses. Looking at the industry sample, it became apparent that storms and flooding pose the highest risks for supply chains while the average temperature increase and extreme heat were mentioned least often.

As for the second question regarding adaptation options, trade policies including elimination or reduction of import tariffs and the adjustment of trade relations was mentioned most frequently regarding the agricultural sample. However, adaptation planning and coordination were identified as relevant adaptation options for both sectors. Examples are the "strategic coordination to build systemic resilience of the food system" (ibid.) in agriculture and "more active dialogue between policy, business and insurance communities, informed by new research" (ibid.) in the industrial sector. Yet, in the latter this category was outnumbered by the category of knowledge creation including awareness-raising, capacity building and knowledge sharing amongst others.

Concerning the key adaptation actors, governmental actors are mentioned most frequently for both samples followed by the international community in the agricultural and research and other businesses in the industrial sample. According to the authors, the role of research is to help to translate climate projections in impacts on and chances for the industry. Regarding the

place of intervention, for the agricultural sector building resilience at the place of origination of the hazards is mentioned most often followed by the sphere of global governance structures in which adaptation planning and coordination, trade policies and other interventions can take place. Good governance is also identified to be the key point of intervention for the industry. However, the authors acknowledge that initiatives for adaption which create spill over effects are difficult to develop on a cross-border or even global level (ibid.).

In the light of the COVID-19 crisis, Ringsmuth et al. (2022) conducted a literature review which happened under the basic premise that the reactions to and impacts of the global pandemic offer valuable insights for useful transboundary adaptation strategies towards another global crisis, namely climate change. After a recap of the effects of the COVID-19 pandemic on health, socioeconomic inequalities (e.g. regarding the distribution of vaccines) and the economy amongst others, the authors turn to the advantages and risks that come with a globally interconnected world. While information can spread across the globe very quickly and the international community is able to support individual states in case of natural disasters on the one hand, the lifestyles that come with a globalised world foster exploitation of resources and climate change. Moreover, globalisation is based on complex networks and supply chains. Turning to the concept of resilience, the authors aim at describing necessary capacities to increase the worlds resilience to shocks: "It requires the development of resilience measures that include incentives to enable networks of government, market actors and civil society to co-generate timely, flexible, and actionable solutions (e.g. cost/benefit standards that factor in future generations' costs and benefits)" (ibid.).

According to the authors, "[t]he pandemic has shown the importance of impact monitoring and openly sharing data across boundaries for building resilience. This enables faster detection, earlier notification to others, and more informed management of cascading impacts. It also allows experts around the world to research challenges that arise, analyse associated risks, and share their findings for collective benefit" (ibid.). One result was the proposal of the European Commission to build a global surveillance system for potential pandemics which allows to share data as early as possible. The authors suggest to invest in a similar monitoring system for climate change. However, monitoring is not enough since climate change is already happening and adaptation measures must come into place. "To be sustainable, such investment would also have to be accompanied by far-reaching reforms in areas such as taxation, subsidy and environmental regulation. Adoption of such policies at the scale and rate required for adequate climate action has been deliberately delayed and also hindered by misinformation about climate change, particularly through nontraditional, digital media. Recent research has found that lower susceptibility to misinformation about both COVID-19 and climate change is associated with higher risk perception, higher capacity to think deliberately and critically, a tendency to update prior beliefs based on new evidence, and higher trust in scientists and mass media" (Ringsmuth et al. 2022).

Returning to the key issue to improve transboundary climate risk management, the authors state first that the systemic nature of climate impacts needs to be considered when assessing climate risks. Thus, cross-sectoral and cross-border mapping of climate impacts should be enhanced to better understand coherences and to be able to develop plausible impact chain scenarios. Moreover, goals of climate adaptation plans should be redefined "including a wider definition of resilience and the targeted scope of these actions" (ibid.). Finally, a system to "establish responsibility for systemic risks" (ibid.) should be introduced. Second, it should be acknowledged that not every climate change impact can be predicted through models. Rather, models should "account adequately for systemic complexity, and adopt adaptive risk management strategies that embrace uncertainty" (ibid.). Moreover, risk management

strategies should build on experiences from earlier crises such as the COVID-19 pandemic. Finally, resilience should be built on several, interconnected levels: "Resilience against system shocks is desired but difficult to achieve. A redefinition of strategic economic objectives can be helpful: from an efficiency-focused paradigm towards a forward looking, multi-objective approach that takes into account social and intergenerational equity" (ibid.). As one incentive, the authors mention the utilization of COVID-19 recovery packages to meet interconnected goals to adapt to climate change.

3.4 Research gaps

Even though indirect or spill-over effects of climate change are already mentioned in international reports from the IPCC and the EEA, there are only few studies that are considering them when studying, for example, global trade (Liu et al. 2013), supply chain risk management (Abe and Ye 2013) and climate change impacts across geographical and administrative borders in today's most interconnected world (Benzie et al. 2017; Füssel 2017; Dell et al. 2014; Kumar and Yalew 2012).

It is also still not clear how gradual climate changes will interact with growing extreme climate events, along the outcomes and the adaptive capacities of agriculture and food systems (Challinor et al. 2016). Therefore, the identification of linkages between different societal teleconnections and among different types of climate change impacts is urgent. However, quantifying teleconnections is most of the times a complex task, and therefore it remains as a research gap across reports and studies (Moser and Hart 2015).

In the analyses discussed above, risks in the trade sector are mostly selected in regards to the monetary trade volume, thus overlooking other risks factors such as goods that are difficult to procure or strategic need of goods for daily livelihood, such as certain staple foods.

There are specific knowledge gaps in the topics of food security related to poor harvest within the EU, cascading effects on EU infrastructure as well as possible financial crisis (Füssel 2017; Benzie et al. 2017). Liverman (2016) points out further knowledge gaps within the study of economic effects of climate change, and that is the assessment of the manufacturing and services sectors. Even though these processes take place in controlled environments, contrary to agriculture and fishery for example, they are still proven to be vulnerable to climate events. The manufacturing and service sectors have been impacted by climate events in the past, whereas impacts on the manufacturing processes by hurricanes, difficulties in stock temperature, or interruption in supply chains by floods. Among these sectors, textiles, auto and electronics, retails and IT are rarely mentioned and even though the topic of agriculture and food security is frequently discussed, very few studies follow commodity chains to assess the food wholesale and retail sector (Liverman 2016, pp. 176–178).

In that sense, "the globally connected food system is a powerful example of how even when climate has some negative effects on local agriculture, farmers can still benefit if things are worse elsewhere and they can obtain higher prices. Those studies that focus only on yields, or which do not take account of traded goods and global price signals are providing inaccurate insights into climate impacts in a globalized world. Several recent projects are starting to look further at the need for multiregional climate assessments as they relate to international markets (Barsugli et al. 2013; Winkler et al 2010; Liu et al 2013)" (Liverman 2016, p. 180).

Further research is also needed on the long-term impact and recovery of supply chains, including case studies on automotive parts and electronic products which represent key global supply chains (Abe and Ye 2013, p. 582).

Whilst there is general consensus on the importance of understanding the global supply chain and its vulnerability to climate change, little attention has been paid to actually analysing this particular connection (Andreoni and Miola 2014). Still, some research has already advanced the study of this phenomenon. In this context, Andreoni and Miola (2014) propose a framework for approaching the topic considering data and methodologies from previous studies and a discussion of main concepts and indicators that can provide a useful baseline for further research within particular cases. The variables to consider refer to factors that determine climate change vulnerability of supply chains, types of climate impacts on supply chains – which can be direct or indirect – and then elements to be considered as factors influencing the magnitude of impacts which range from interruptions in strategic sectors, to social, economic and governmental conditions and responses to impacts.

4 Conclusions for analyzing transboundary climate risks in Germany

Based on the sources and discussions above, the following variables seem important for any future analyses of transboundary climate risks in Germany that focus on traded goods and supply chain. In order to analysis such risks for one or more traded goods, it is important to consider…

- Economic and trade related aspects
    - Value of the good: prioritizing and categorizing goods according to their total values to focus in on goods with a high relevance for the economy.
    - Concentration of supplying countries: looking at how many countries or suppliers offer or have offered the good in questions can provide some estimate how difficult it might be to substitute a good if certain supply chains have been interrupted.
    - Warehousing: can the good be stored well? What are possible storage capacities and practices?
- Climate vulnerability related aspects
    - Overall distance travelled of the good: the distance travelled can be a proxy for the exposure to climate-related risks along the way.
    - Vulnerability of the origin country: exposure to climate risks in the country where the good is sourced.
    - Vulnerability of the countries/geographical areas through which the good is passing thorough: Supply chains are complex and diversified processes where raw materials are transformed and distributed through multiple channels. These routes and processing countries can also be subject to climate impacts.
    - The good's vulnerability to climate impacts: e.g. especially for food products there is a certain dependency on climatic conditions but industrial products as well depend on certain environmental factors, e.g. water availability, which can be affected by climate change.

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