Climate Change Impact Chains: A Review of Applications, Challenges, and Opportunities for Climate Risk and Vulnerability Assessments

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ABSTRACT: Shifting from effect-oriented toward cause-oriented and systemic approaches in sustainable climate change adaptation requires a solid understanding of the climate-related and societal causes behind climate risks. Thus, capturing, systemizing, and prioritizing factors contributing to climate risks are essential for developing cause-oriented climate risk and vulnerability assessments (CRVA). Impact chains (IC) are conceptual models used to capture hazard, vulnerability, and exposure factors that lead to a specific risk. IC modeling includes a participatory stakeholder phase and an operational quantification phase. Although ICs are widely implemented to systematically capture risk processes, they still show methodological gaps concerning, for example, the integration of dynamic feedback or balanced stakeholder involvement. Such gaps usually only become apparent in practical applications, and there is currently no systematic perspective on common challenges and methodological needs. Therefore, we reviewed 47 articles applying IC and similar CRVA methods that consider the cause–effect dynamics governing risk. We provide an overview of common challenges and opportunities as a roadmap for future improvements. We conclude that IC should move from a linear-like to an *impact web*–like representation of risk to integrate cause–effect dynamics. Qualitative approaches are based on significant stakeholder involvement to capture expert-, place-, and context-specific knowledge. The integration of IC into quantifiable, executable models is still highly underexplored because of a limited understanding of systems, data, evaluation options, and other uncertainties. Ultimately, using IC to capture the underlying complex processes behind risk supports effective, long-term, and sustainable climate change adaptation.

KEYWORDS: Climate change; Adaptation; Communications/decision making; Risk assessment; Vulnerability

1. Introduction

With climate change progressing, policy makers and decision-makers are faced with an increasingly pressing need for climate action plans and adaptation strategies. These need to be based on accurate, evidence-based information on the causes and effects of climate change. The importance of focusing on climate change causes was introduced as early as 1987, in the famous United Nations World Commission on Environment and Development (WCED) Report "Our Common Future" (WCED 1987), recommending a "shift from an effect- towards a cause-oriented approach to environmental policy."

Climate change risk and vulnerability assessments (CRVA) are one way to provide policy makers with the necessary information. They identify the main risk drivers and inform climate change adaptation (CCA) and disaster risk reduction (DRR) interventions and decision-making.

Concepts and definitions utilized in CRVA are constantly evolving to better meet the challenges of capturing and describing complex real-world processes. Central to this evolution are the conceptualizations of risk and vulnerability, which have recently undergone a consolidation process among the scientific communities (Kienberger et al. 2016). While the Intergovernmental Panel on Climate Change's (IPCC) Third Assessment Report (AR3; IPCC 2001) and IPCC AR4 (IPCC 2007) described assessment frameworks for climate change vulnerability, the Special Report of the Intergovernmental Panel on Climate Change (SREX; IPCC 2012) and IPCC AR5 (see IPCC 2014; Huq et al. 2014) adopted a risk assessment framework for climate change impacts. Other influential and related works include the Crichton's Risk Triangle (Crichton 1999) the Climate Vulnerability and Capacity Analysis Handbook (Daze et al. 2009) and the Methods for the Improvement of Vulnerability Assessment in Europe (MOVE) framework (Birkmann et al. 2013).

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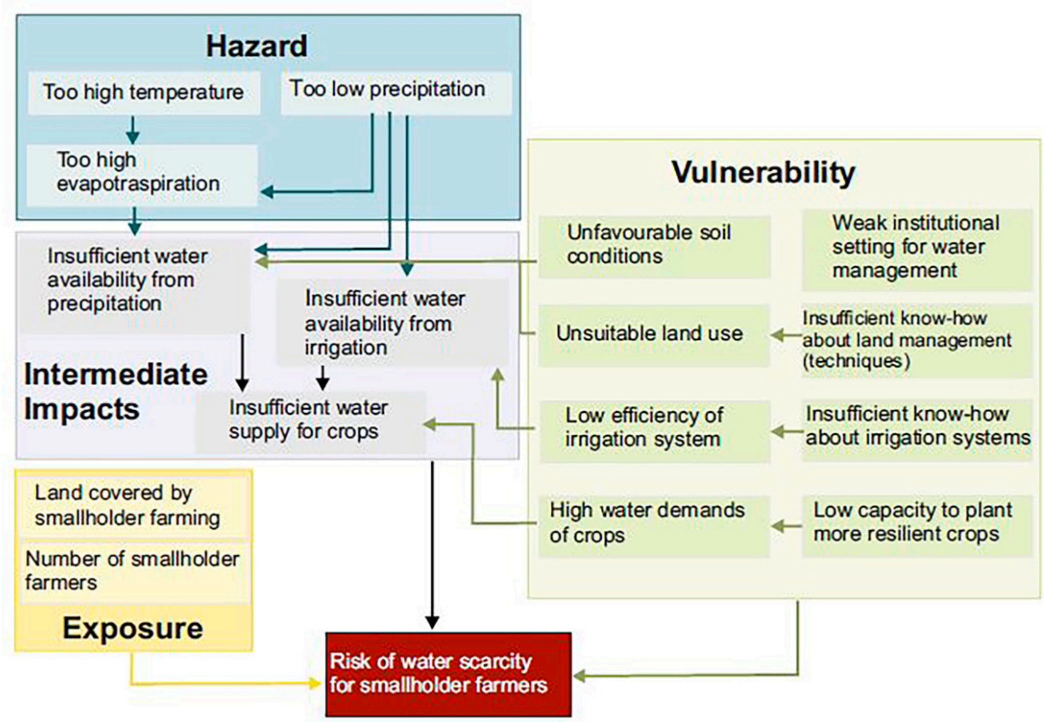

FIG. 1. An example impact chain for the water scarcity risk of smallholder farmers. Illustrations like this are usually developed jointly with stakeholders in a participatory manner. The impact chain method provides a reference framework for the assessment.

Moreover, other older studies, and more recent ones as well, support the integration of CCA and DRR initiatives with the Sustainable Development Goals (SDG) to increase resilience (Berkes et al. 2000) while also achieving sustainable development (Morchain and Robrecht 2012; United Nations 2021). The IPCC AR4 (IPCC 2007) defined risk as consisting of vulnerability and exposure, with vulnerability described as "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." In 2014, the IPCC AR5 adopted the risk concept from the DRR community, which understands risk as the interaction of vulnerability, exposure, and hazard.

The particular CRVA method we review here is described in the Vulnerability Sourcebook (Fritzsche et al. 2014), and its supplements (Zebisch et al. 2017), as well as in Zebisch et al. (2021). Throughout this article, we will refer to it as the impact chain (IC) method. IC is a young method with several recent international applications (e.g., Becker et al. 2014; Kabisch et al. 2014; Kienberger et al. 2016; Lückerath et al. 2018; Rome et al. 2019, 2018; Schneiderbauer et al. 2020). It is a mixed-methods approach that is strictly oriented toward its suitability for adaptation planning and allows the integration of different data sources and participatory appraisals. It presents step-by-step guidelines for assessing complex risk systems and offers the opportunity to integrate intermediate risks and impacts (Zebisch et al. 2021). The IC method was first developed by Schneiderbauer et al. (2013) to assess climate vulnerability in the Alps. In 2014, the concept was catalyzed and integrated into the Vulnerability Sourcebook on climate vulnerability assessments in the context of international cooperation (Fritzsche et al. 2014) and has since been applied in numerous studies evaluating the vulnerabilities/risks related to climate change. The IC method also provided the conceptual basis for Germany's national climate vulnerability assessment (Buth et al. 2017) and climate risk assessments in the context of ecosystem-based adaptation (Hagenlocher et al. 2018). The IC method is now partially covered in the International Organization for Standardization 14092 standard (International Organization for Standardization 2019), which provides step-by-step guidelines for CRVA.

The IC method is a conceptual framework used to capture the most relevant factors contributing to a specific risk. It structures the risk factors based on the IPCC AR5 risk definition, dividing risk into the hazard, exposure, and vulnerability factors (IPCC 2014; Huq et al. 2014). As exemplarly shown in Fig. 1, the IC is always focused on the risk stemming from a specific hazard (e.g., excessively high temperature). Exposure factors usually refer to a specific sector or a group of affected people (e.g., smallholder farmers) in a specific geographical setting. The intermediate impacts usually affect biophysical elements (i.e., primarily related to the hazard component), successively leading to the final human-centered risk. The vulnerability factors represent the nonclimatic dimensions that either increase or decrease the risk for the exposed sector or

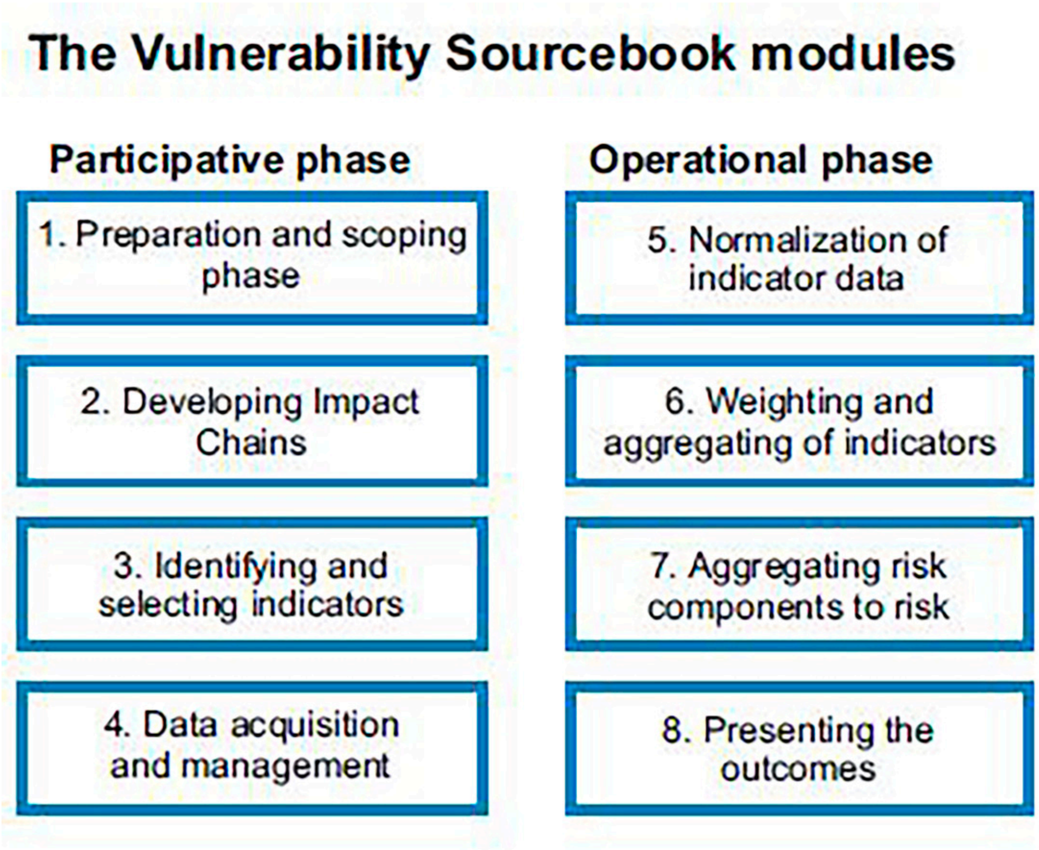

FIG. 2. The Vulnerability Sourcebook modules can be considered as consisting of two phases, as shown here.

group. Determining the most influential vulnerability factors is key to a meaningful, context-specific IC and requires local knowledge and a profound understanding of the individual driving forces (Fritzsche et al. 2014; Zebisch et al. 2017).

Users of the Vulnerability Sourcebook follow a stepwise process, which is exemplified in Fig. 2. It starts with a participatory, qualitative phase, delineating the principal risk factors and continues with an operational phase, quantifying them through indicators. During the participatory phase, ICs are usually developed jointly with stakeholders such as policy makers and decision-makers, experts and/or users in participatory workshops (Becker et al. 2014; Greiving et al. 2015; Kabisch et al. 2014; Kienberger et al. 2016; Lückerath et al. 2018; Rome et al. 2019; Schneiderbauer et al. 2020). Including a diverse group of stakeholders is intended to cover a wide area of knowledge and provide location-specific insider information and data. Including stakeholders is also intended to spark mutual learning, build trust, and increase capacities for planning adaptation measures. Stakeholder knowledge is usually captured through workshops, where the workshop participants determine, systemize, and prioritize the factors that contribute to the risk under consideration. The results of the participatory phase serve as a reference framework to translate risk factors into indicators. For each indicator, (spatial) data are retrieved wherever possible. The indicator data are usually normalized, aggregated, and weighted, as suggested in Zebisch et al. (2017), allowing to combine information related to the hazard, exposure, and vulnerability components into a single risk indicator. This result yields location-dependent risk scores that are presented alongside the narrative results from discussions, interviews, and other relevant workshop outcomes. This should enable the identification of priority areas for adaptation interventions (Zebisch et al. 2021).

We review the IC method within the context of the project "Unpacking climate impact chains. A new generation of action- and user-oriented climate change risk assessments (UNCHAIN)" (https://www.unchain.no), which was launched in 2019. The projects central research objectives are the improvement of the IC method through a range of innovations. These include standardized procedures for integrating a dynamic, rather than static, representation of risk and its contributing factors. Furthermore, the project develops standardized procedures for knowledge coproduction through stakeholder participation for integrating indirect and transnational impacts, socioeconomic scenarios, and uncertainties. This paper focuses on the handling of the dynamics and cause–effect relationships between risk factors, both in past applications of the IC method, as well as in other, similar CRVA applications. Similar CRVA applications include qualitative and quantitative approaches, as well as combinations of both. We expect qualitative approaches to share conceptual similarities with the participatory phase of the IC method, while we expect quantitative approaches to have similarities with the operational assessment phase. Both IC phases currently show methodological gaps concerning a dynamic representation of risk. These gaps might be closed in future scientific work by incorporating methods and solutions from related approaches. The result of our review is a shared knowledge base for researchers and modelers. We are particularly interested in respective application contexts and the challenges and limitations experienced by users. We are also interested in the opportunities users see in IC and related CRVA to carve out possible future development pathways for the IC method. Further improving and refining the IC method is intended to facilitate even more targeted and sustainable climate change adaptation that addresses causes of risk.

As part of the UNCHAIN project, we herein review scientific literature describing past IC applications and similar CRVA applications that include cause–effect risk dynamics. While the IC method has been widely applied (e.g., Becker et al. 2014; Kabisch et al. 2014; Kienberger et al. 2016; Lückerath et al. 2018; Rome et al. 2019, 2018; Schneiderbauer et al. 2020; Zebisch et al. 2021), a thorough review does not exist to date. By doing this, we follow the suggestion of Zebisch et al. (2021) to move from relatively linear and sectoral impact chains to "impact webs, which include feedback relations and cross-connections." We understand *cause–effect risk dynamics* in this context as the idea that risk factors create a system whose elements share cause–effect relationships. This means changes in one part of the system can impact other parts of the system (Dilling et al. 2015), a factor that has received little attention so far in risk/vulnerability assessments (Jurgilevich et al. 2017). In past IC applications, risk factors were considered to influence the final risk, but not each other. We want to move from this understanding toward an understanding where the risk contributing factors influence the final risk and each other, thus forming an impact web. The challenge of integrating cause–effect dynamics into risk and vulnerability assessments has also been addressed by, for example, Jurgilevich et al. (2017) and Ford et al. (2018).

2. Methods: Literature review

The identification of scientific literature consisted of two parts:

(i) *A focused search for IC applications*: Because of the specific focus of this review, we manually added particularly relevant articles involving ICs by contacting IC users associated with the UNCHAIN project. These articles are highlighted in the results section to maintain workflow transparency.

(ii) *Querying online databases for CRVA applications that include risk dynamics*: For the literature selection and evaluation, we applied the same procedure as Haddaway et al. (2015), which is based on Dawkins et al. (2019), who present guidelines for a systematic literature review. The applied procedure consisted of four steps (shown in Fig. 3 and described in more detail below) to reduce selection biases, increase transparency, consistency, reproducibility, and procedural objectivity.

Step 1 of part ii consists of specifying inclusion and exclusion criteria and identifying key terms to query scientific databases (see Fig. 3). Step 2 involves querying scientific databases based on key terms: The online databases Scopus (https://www.scopus.com/) and Web of Science (https://apps.webofknowledge.com/) were considered adequate because of their large collection of peer-reviewed literature on the social and environmental sciences (Landauer et al. 2015). The search had no restrictions on the year of publication and was conducted in December 2019. We did not include gray literature because of the large number, differing quality, extent, and often poor indexing (e.g., deliverables from national, European, and international research projects) and to keep the workflow transparent and reproducible. Steps 3a and 3b involve collecting metadata and abstracts for all matching articles and screening them against the inclusion and exclusion criteria. As shown in Fig. 4, the database queries returned 232 unique articles. The abstract screening left 62 articles that fulfilled all prerequisites (see the appendix for a detailed overview of the selection decisions). In step 4, we coded the articles for application contexts, methods employed, key challenges, and opportunities in the text analysis software MAXQDA.

Fifty-three articles were retrieved as full text, and nine were inaccessible. Twelve articles were excluded during the coding phase. Six were additionally added as a result of the focused search on IC applications. This resulted in a total of 47 reviewed articles. To ensure the systematic extraction of information, all texts were evaluated on the basis of a coding scheme, which differentiated application contexts, methods used, information sources, and challenges and opportunities. The online supplemental material contains a spreadsheet with detailed information on the 47 articles and these aspects of the coding scheme. Articles that were found unfitting during the coding phase were tagged as such and removed.

Table 1 shows the research questions (RQ) in which we were interested. We did not predetermine the categories/definitions; rather, they emerged from a circular learning process during the reading and coding phase.

3. Results

a. Contextual and background information (RQ 1.1–1.4.)

RQ 1.1 is *geographical distribution*. The reviewed CRVAs have a geographical bias toward European, and, to a lesser extent, toward African and Asian countries (Fig. 5). The United Kingdom stands out in particular, with 10 applications focusing on it.

RQ 1.2 is *assessment scale*. As shown in Fig. 6, the assessments are very heterogeneous, with about one-half of them focusing on various subnational scales and the other one-half focusing on a national scale or above. CRVA applications dealing with the critical risk of infrastructure failure predominantly focused on single assets, for example, dam or bridge failure (Dikanski et al. 2016; Evans et al. 2018; Fluixá-Sanmartín et al. 2019) or infrastructure networks (Pant et al. 2016). Subnational-scale assessments focusing on water

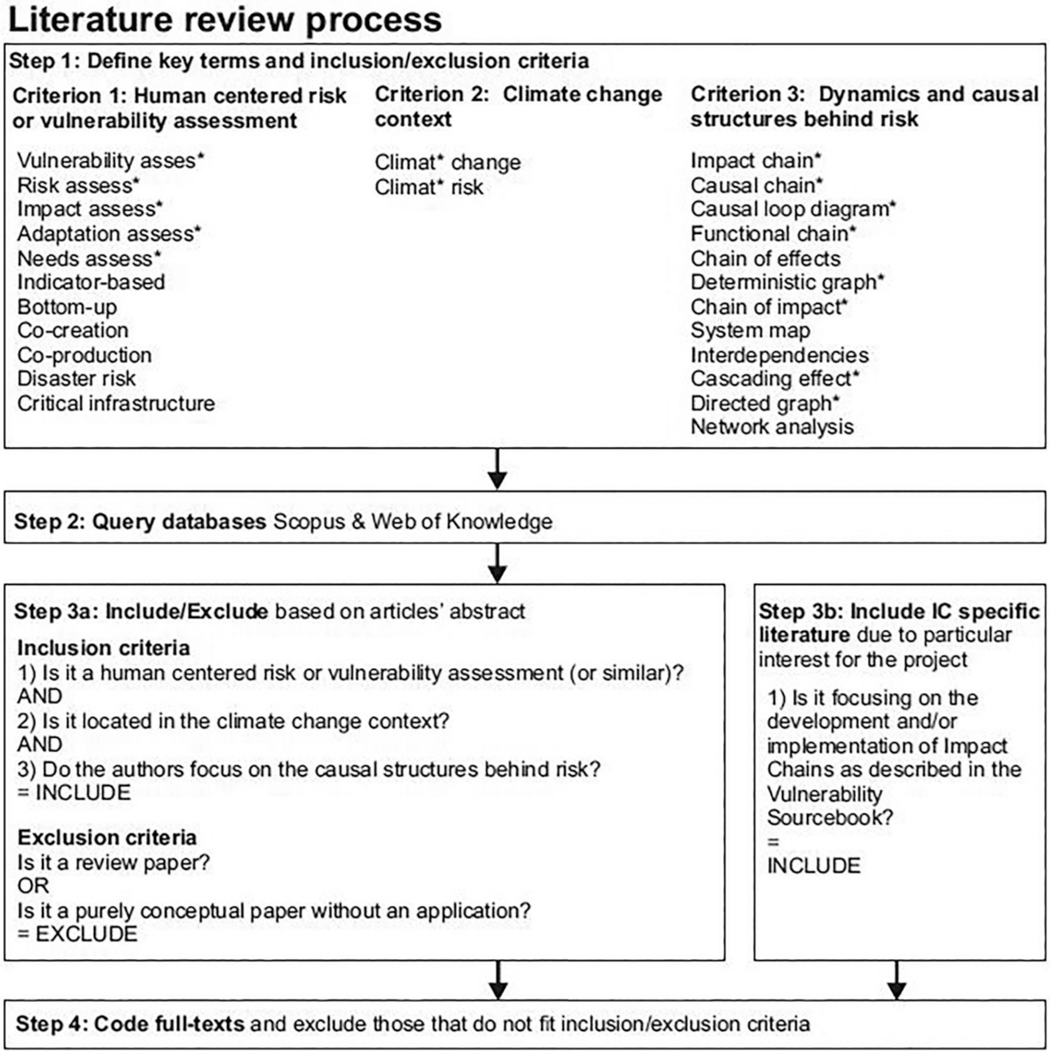

FIG. 3. The distinct steps of our literature review process.

access/availability and/or quality were the most common (Caniglia et al. 2016; Kabisch et al. 2014; Moglia et al. 2013; Schneiderbauer et al. 2020; Sperotto et al. 2019).

RQ 1.3 is *assessed hazards*. The analysis of the type of hazards assessed showed a range of results, spanning climate hazards (e.g., storms or droughts) and secondary climate impacts (e.g., water quality deterioration) on different levels of hierarchy (e.g., changed precipitation patterns versus coastal erosion). Figure 7 shows the number of times a hazard or impact has been addressed within the reviewed articles. With over 20 applications, storm surges and (coastal) floods ranked first, followed by droughts. Over 10 articles address climate change-related hazards without further specification.

RQ1.4 is *risk concepts*. Figure 8 shows that the concept that the CRVA define as risk is not consistent throughout all articles. The risk concept promoted in the IPCC AR4 (vulnerability plus hazard) and the IPCC AR5 definition (vulnerability, exposure, and hazard) have been used in parallel since the IPCC AR5 launch in 2014. This conceptualization is widely covered in articles, but it has not yet completely replaced its predecessor. However, the greater share of reviewed articles does not refer to any of the IPCC promoted definitions ("other/none mentioned"). For example, some articles conceptualize risk as the consequences arising from crossing a limit, such as the risk of failure of a single piece of critical infrastructure, for example, dams or bridges (Dikanski et al. 2016; Fluixá-Sanmartín et al. 2019; Thacker et al. 2018; Tonmoy and El-Zein 2013).

b. *Which information sources were used in combination with which dynamics-focused methods? (RQ 2)*

The reviewed articles employed a broad range of different methods, which we assigned to three methods clusters: 1) IC-based approaches, 2) qualitative models of cause and effect, and 3) quantitative models and simulations. However, few of the reviewed CRVA approaches were purely

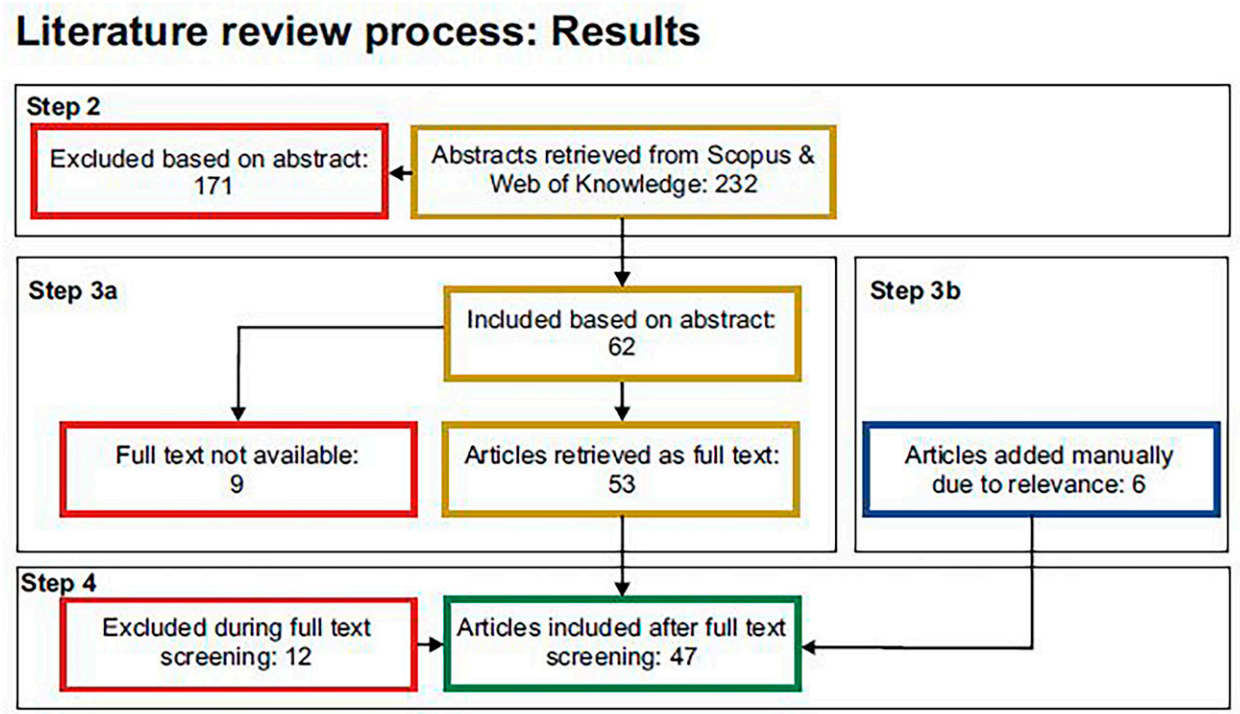

FIG. 4. An overview of the literature review process. The numbers in the yellow boxes indicate the number of articles that remained after each step, and the red boxes provide information about the respectively excluded texts. The blue box shows that six articles were added manually, and the green box gives the number of articles included in the final review.

qualitative or purely quantitative. When articles described a mix of methods, we assigned them to both clusters 2 and 3. Articles that applied the IC method as described in the Vulnerability Sourcebook were assigned to cluster 1. The commonality of the articles clustered in *qualitative models of cause and effect* was that they detailed their knowledge creation process of cause and effect. The commonality of the articles clustered in *quantitative models and simulations* was that they included any kind of quantitative calculation. The logic behind classifying the methods into a specific cluster was adapted from Kelly et al. (2013), Ouyang (2014), and Jurgilevich et al. (2017).

Furthermore, we identified four groups of information sources: 1) extensive literature research and reviews; 2) modeled data, usually used to integrate possible future developments or to fill data gaps; 3) measured or surveyed quantitative data; and 4) expert and stakeholder knowledge, acquired through workshops, interviews or surveys. Figure 9 shows the combinations of methods and information sources and the number of times that they were applied.

The following paragraphs will provide an overview of the method clusters and their information sources.

1) IMPACT CHAIN-BASED APPROACHES: SPATIALLY EXPLICIT, INDICATOR-BASED ASSESSMENTS WITH PARTICIPATORY KNOWLEDGE CREATION

Articles classified as "IC-based approaches" followed the assessment steps described in the Vulnerability Sourcebook. The participatory phase includes workshops with experts, stakeholders and/or affected communities, supported by information from existing literature, models, maps, graphics, etc. The operational phase is usually a spatially explicit, indicator-based assessment aiming to highlight geographic areas of high risk. This phase is informed by the outcomes of the participatory phase, measured or surveyed data, and modeled data. The IC-based papers were identified through the focused search and included Hussain (2014), Becker et al. (2014), Kienberger et al. (2016), Kabisch et al. (2014), Lückerath et al. (2018b), Rome et al. (2018), Rome et al. (2019), and Greiving et al. (2015).

2) QUALITATIVE MODELS OF CAUSE AND EFFECT: UNDERSTANDING SYSTEM LINKS THROUGH SHARED KNOWLEDGE

Articles focusing on the qualitative representation of cause and effect typically employed methods similar to those implemented in the participatory phase of the IC. As shown in Fig. 9, most articles integrated expert and/or stakeholder knowledge. The second most employed information source involved existing literature, while measured, surveyed, and modeled data played a minor role.

The employed methods show conceptual similarities with the IC method and include inter alia deterministic graphs (Lissner et al. 2012), causal loop diagrams (Olabisi et al. 2018; Tonmoy and El-Zein 2013), network flowcharts (Yokohata et al. 2019), fuzzy cognitive maps (Romero-Lankao and Norton 2018), causal chains/loops (Anandhi et al. 2018), or impact chains/

TABLE 1. Our research questions (RQ), including the coded categories along with their definitions.

Indexing	Research questions	Categories/definitions
RQ 1.1	How were the reviewed CRVA distributed geographically?	National level (referring to a country or nation)
RQ 1.2	On which sectors and administrative scales were they focused?	Sectors: agriculture, food security; critical infrastructure; environment, urban living; water; multiple/administrative scales: global (involving the whole world), transnational (extending beyond national boundaries), national (referring to a nation or country), subnational (relating to a region or group within a nation), agglomeration/city (large, densely populated area), and local (relating to a town or other comparatively small district)
RQ 1.3	Impacts from which hazards were assessed?	Water related (e.g., storm surges and flooding); temperature related (e.g., heat waves and cold spells)
RQ 1.4	How was *risk* conceptualized?	IPCC 3 and 4, IPCC 5, other, or none
RQ 2	Which information sources were used in combination with which dynamics-focused methods?	Information sources: experts/stakeholders, measured or surveyed data, modeled data, extensive literature review/ methods: impact chains, qualitative models of cause and effect (e.g., causal loop diagrams), and quantitative models and simulations (e.g., system dynamics)
RQ 3	What challenges, methodological gaps, and opportunities were experienced with different methods?	Relating to stakeholder involvement, cause-effect identification, quantification of system elements and interrelations, communication of concepts and results, data gaps, and evaluation and validation options

chain of impacts, but do not reference the Vulnerability Sourcebook (Lissner et al. 2012; Lomba-Fernández et al. 2019; Steininger et al. 2016; Tapia et al. 2017).

For example, Romero-Lankao and Norton (2018) developed fuzzy cognitive maps in collaboration with stakeholders, a technique similar to the IC method or causal loop diagrams used to display and acquire causal knowledge. They analyzed the interdependencies that mediate the cascading negative consequences on people of food–energy–water systems triggered by flooding events in Boulder, Colorado.

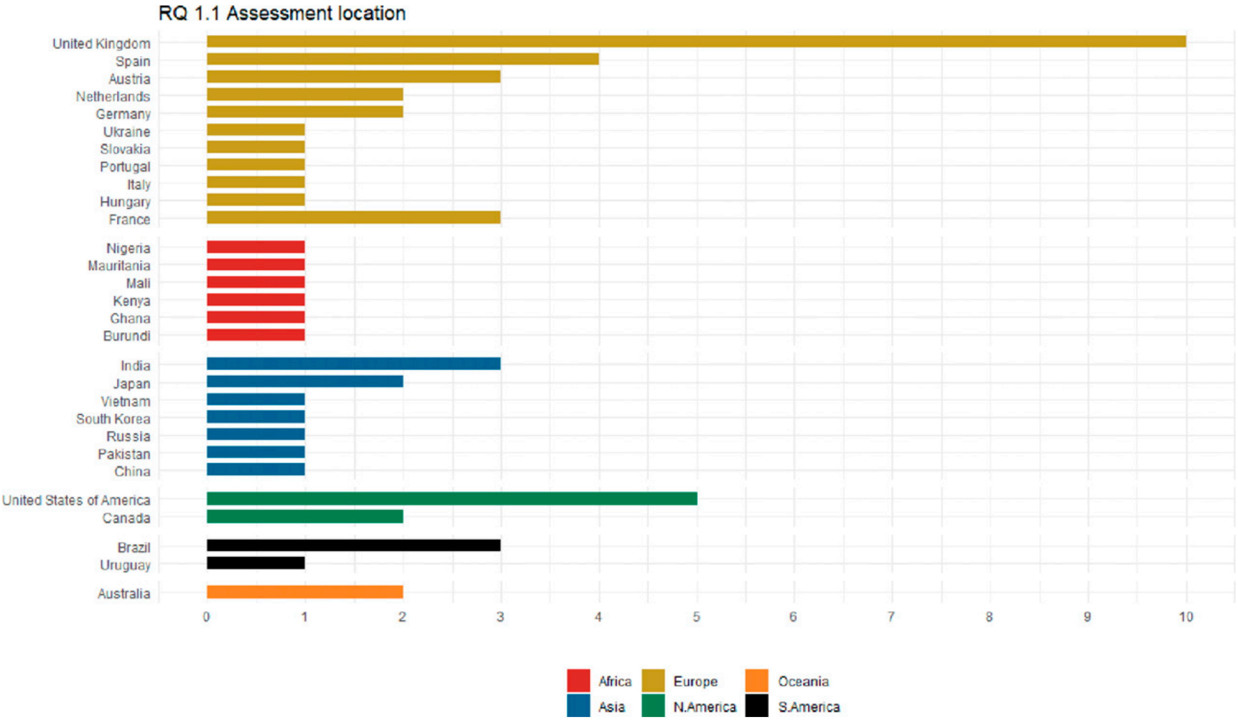

FIG. 5. The number of articles per geographic location.

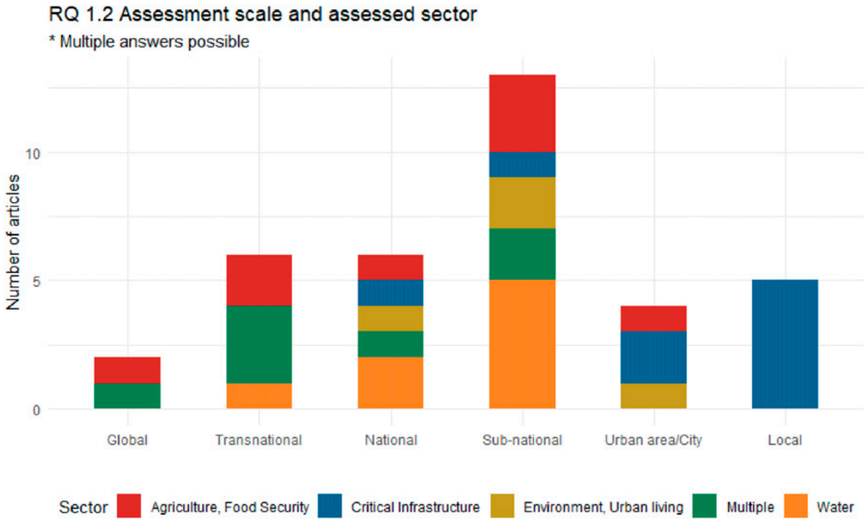

FIG. 6. Assessment scales ranged from global to individual pieces of infrastructure. Most articles assessed risk on a subnational scale, followed by national and transnational scales. Few articles also assessed risk on the city level.

Olabisi et al. (2018) developed causal loop diagrams in a series of stakeholder workshops to identify sources of climate risk in different parts of West Africa. Kang and Park (2018) identified trends in climate change risk indicators by using network analysis fed by text-mining results from South Korean newspaper articles published over the course of 24 years. Their results provided policy response and urban planning implications to reduce climate change risk in South Korea. Debortoli et al. (2018) used network analysis, fed by information extracted from literature, to assess the vulnerability of Inuit communities in the Canadian Arctic.

3) QUANTITATIVE MODELS AND SIMULATIONS: PROJECTIONS OF RISK THROUGH DATA AND NUMBERS

This cluster includes articles focusing on quantitative models, simulations, and scenario-based approaches. This encompasses a broad range of approaches, including system dynamics-based

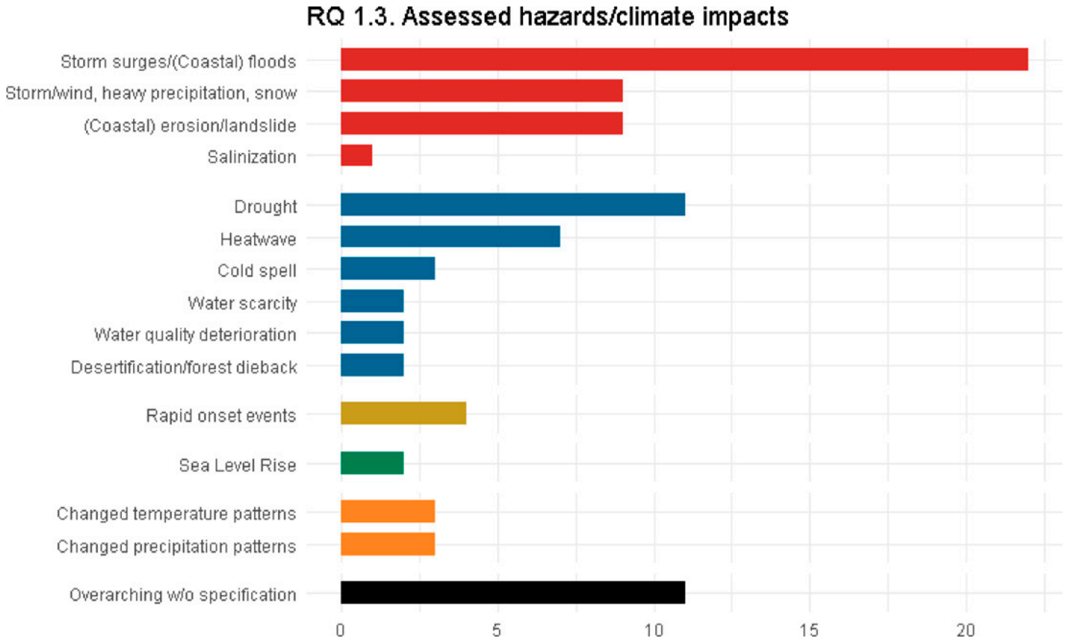

FIG. 7. The hazards and/or climate impacts with which the reviewed articles were concerned. More than 20 articles dealt with storm surges and/or (coastal) floods, followed by droughts.

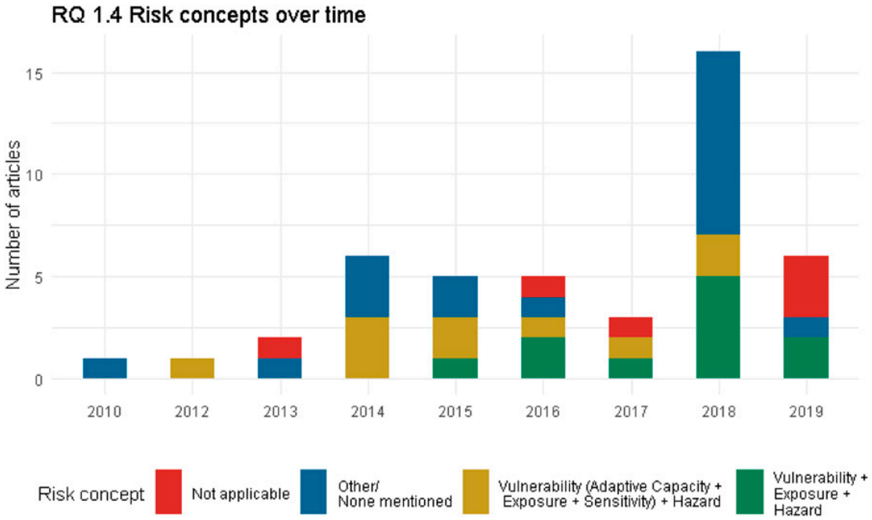

FIG. 8. The year of publication for the reviewed articles, colored according to the risk concepts used, if any. The IPCC AR5, which describes risk as a function of vulnerability, exposure, and a hazard (shown in green) was published in 2014.

approaches (Gies et al. 2014; Tonmoy and El-Zein 2013), economic theory–based approaches (Bierkandt et al. 2014; Lapola et al. 2018; Reilly et al. 2013; Steininger et al. 2016; Thacker et al. 2018), and Bayesian networks (Moglia et al. 2013; Sperotto et al. 2019) or agent-based approaches (Bierkandt et al. 2014). Surveyed and measured data were the most used information sources, followed by modeled data. A few applications also integrated an extensive literature review, while expert and stakeholder knowledge was seldom utilized. In these articles, the process of determining cause–effect relationships was not necessarily the central element. This means the cause–effect knowledge acquisition process is not discussed with the same level of detail in every article. Instead, these articles focused more on the quantification of risk. For example, Steininger et al. (2016) evaluated impact chains where impact models were already available or could be meaningfully transferred instead of generating impact chains from scratch. Gies et al. (2014) developed a system dynamics model coupled with a hydrologic model using historical weather data and literature research to support drought adaptation policies at the Horn of Africa. Pant et al. (2016) established a national vulnerability assessment framework for interdependent infrastructure in the United Kingdom using interdependent network representations of key critical components and their interactions at local and national scales.

c. *What challenges, methodological gaps and opportunities were experienced with different methods? (RQ 3)*

We identified six core challenges, methodological gaps, and opportunities (which are shown in Fig. 10) and will be reported on in sections 3c(1)–3c(6). The first three of them relate predominantly to the cluster *qualitative models of cause and effect*: 1) involving stakeholders and experts, 2) identifying cause–effect relationships governing risk, and 3) communicating concepts and results. The other three relate predominantly to the cluster *quantitative models and simulations.* These are 4) quantifying system elements and interrelations, 5) data gaps, and 6) lacking evaluation options. *Impact-chain-based approaches,* as mixed-methods approaches, report challenges and opportunities pertaining to all aforementioned points and are integrated into each of the six subsections.

1) INVOLVING STAKEHOLDERS AND EXPERTS: IT IS UNDOUBTEDLY ESSENTIAL BUT IT COMES WITH FLAWS

Four of the six IC-application articles mentioned challenges with regard to the participatory involvement of experts and stakeholders. Regular involvement throughout all research phases is time and resource intensive (Greiving et al. 2015; Schneiderbauer et al. 2020) and a diverse group of stakeholders likely has diverging interests and different opinions on the relationships between risk factors (Schneiderbauer et al. 2020). Furthermore, the communication of limitations, uncertainties, and terms and concepts to inexperienced people is described as challenging (Kienberger et al. 2016). Another point to consider is that an IC developed in a group only represents this group's view of risk contributing factors and cause–effect relationships and not necessarily reality (Lückerath et al. 2018). However, the integral role of stakeholder involvement is never challenged, and four papers explicitly list the opportunities of stakeholder involvement, which include the increased legitimacy of results (Kienberger et al. 2016) and the increased self-awareness and ownership through discussions with others (Kabisch et al. 2014).

Six articles from the "qualitative models of cause and effect" cluster mention challenges relating to stakeholder and expert participation. They emphasize that stakeholders are likely to focus primarily on their system of interest rather than

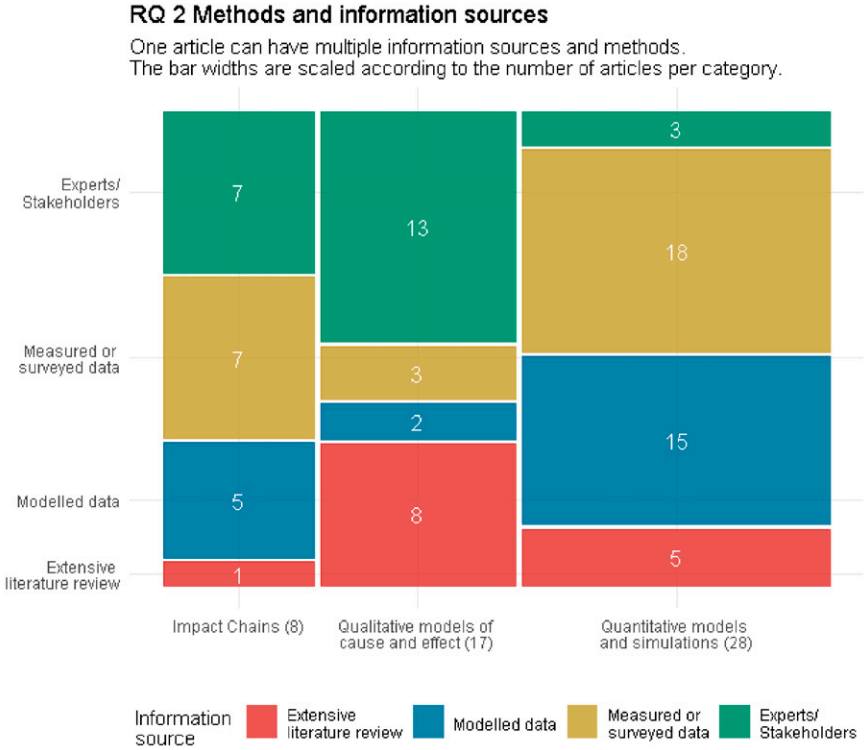

FIG. 9. Impact-chain-based approaches use a balanced mix of modeled data, measured data, or surveyed data and expert/stakeholder involvement, as shown here. An extensive literature review is only once mentioned specifically. The articles that we assigned to the cluster "qualitative models of cause and effect" primarily make use of stakeholder/expert involvement, followed by extensive literature reviews. Modeled and measured/surveyed data are only rarely used. The biggest cluster "quantitative models and simulations" shows the opposite: Measured/surveyed and modeled data are heavily used, whereas stakeholder/expert involvement and extensive literature reviews are the exception.

considering a larger perspective, including interconnections and indirect effects (Romero-Lankao and Norton 2018; Tsavdaroglou et al. 2018). Therefore, it is important to involve stakeholder groups covering all relevant perspectives (Greiving et al. 2015). Furthermore, possible subjectivity, limited knowledge, and limited experience among stakeholders and experts must be kept in mind and compensated for wherever possible (Tsavdaroglou et al. 2018; Greiving et al. 2015; Moglia et al. 2013).

Five articles mention stakeholder and expert knowledge as an opportunity to validate results and reduce uncertainty, for example, in combination with data- or literature-driven assessments (Kang and Park 2018). Moreover, stakeholder knowledge can be employed to verify which adaptation measures would be realistic, feasible, and desired by the communities, which could potentially lower the barriers between research outputs and adaptation action implementation (Greiving et al. 2015, Debortoli et al. 2018). Additionally, the range of perspectives coming from a heterogeneous group of stakeholders is perceived as an intermediate goal and valuable outcome per se (Hussain 2014). Lozoya et al. (2015) call for stakeholder participation as an important condition for successful risk management, while Romero-Lankao and Norton (2018) refer to stakeholder participation as a good means to prepare for and mitigate the impacts of future extreme events.

2) IDENTIFYING CAUSE–EFFECT RELATIONSHIPS BEHIND RISK: WORKING WITH WHAT WE KNOW

A variety of challenges pertain to the identification of the most relevant system elements and their cause–effect relationships, which cannot always be clearly deduced due to insufficient knowledge of the system (Kabisch et al. 2014; Kang and Park 2018; Schneiderbauer et al. 2020). The extent to which this limited insight and understanding of the system poses a problem depends on the purpose of the analysis. On the one hand, if a better general understanding of a system is the objective, ICs can be developed despite knowledge about their limitations (Kabisch et al. 2014). On the other hand, complex systemic interrelations (e.g., transboundary or multi-risks) are sometimes simply neglected or heavily simplified (Espada et al. 2015; Distefano et al. 2018; Steininger et al. 2016).

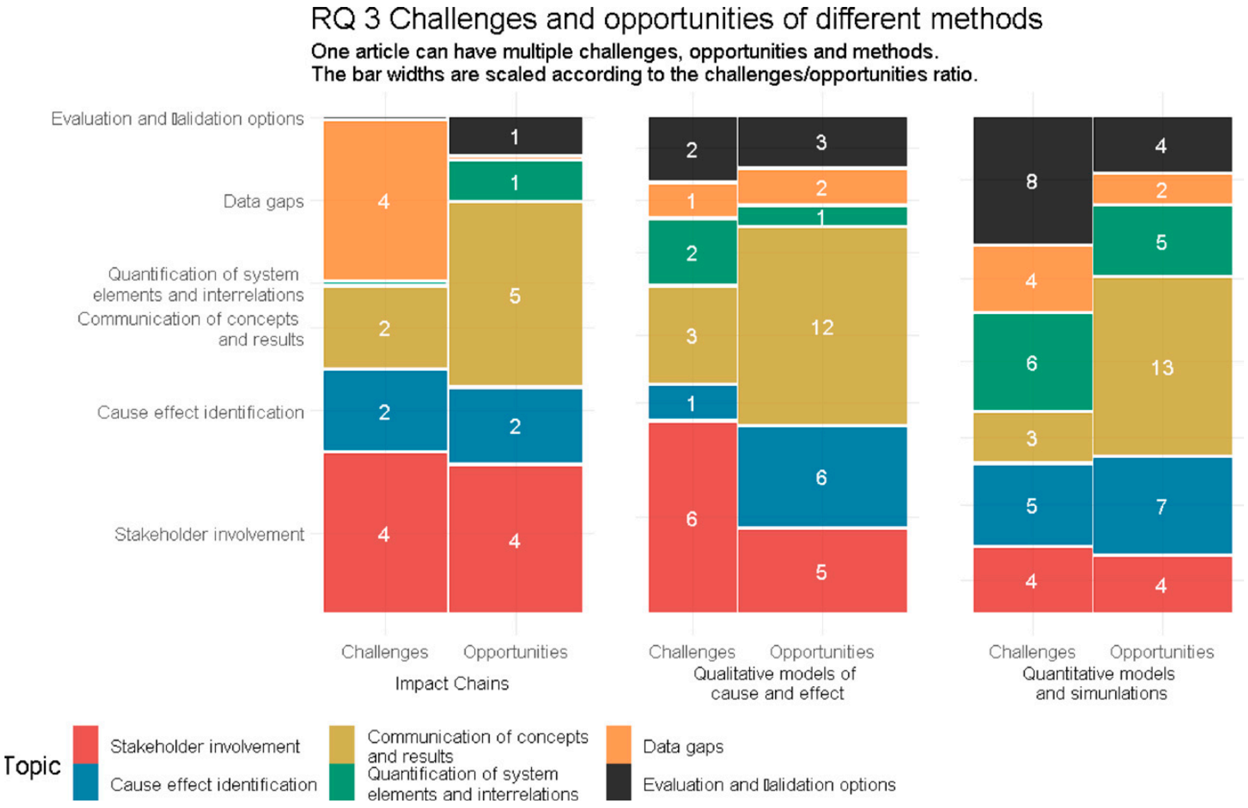

FIG. 10. Impact-chain-based approaches see challenges mainly with stakeholder involvement and data gaps, as shown here. Cause–effect identification and communication of results were both mentioned twice, whereas evaluation and validation options and quantifications of system elements and interrelations were not mentioned. However, they also see opportunities in stakeholder involvement, cause–effect identification, and, primarily, in the IC's ability to communicate concepts and results. The others play minor roles. Notable for the "qualitative models of cause and effect" cluster is that the opportunities clearly outweigh the challenges. Main challenges revolve around stakeholder involvement, whereas main opportunities are again seen in its potential to communicate concepts and results. The main challenges of the "quantitative models and simulations" cluster are the limited evaluation and validation options and the quantifications of system elements and interrelations. The potential to communicate concepts and results is also the main opportunity here, followed by cause–effect identification and quantifications of system elements and interrelations.

3) COMMUNICATING CONCEPTS AND RESULTS: NOT MAKING IT TOO COMPLICATED

The primary potential of all three method clusters is the communication of concepts and results because CRVA results usually provide a direct link to tangible vulnerability and risk factors (e.g., Hedrich et al. 2016; Schneiderbauer et al. 2020) and/or adaptation strategies (e.g., Becker et al. 2014; Dawson et al. 2018; Hedlund et al. 2018; Kabisch et al. 2014; Sperotto et al. 2019).

However, terms and concepts associated with methodological frameworks can be unintuitive when newly introduced (Kienberger et al. 2016) or unclear when they are used differently within different communities (such as the risk definition in the DRR and CCA communities) (Greiving et al. 2015).

Concisely presenting the cause–effect relationships that lead to a final risk is difficult when there are many relationships to consider (Becker et al. 2014). However, Yokohata et al. (2019) found that structuring cause–effect relationships into natural, socioeconomic, and human systems was a good means to increase the stakeholders' understanding of the potential future risks related to their field of activity. The visual representations of ICs are valued as easily understandable conceptual models of the identified relationships, enabling adaptation planning and increasing awareness (Hussain 2014). However, once the represented number of interrelations from risk processes increases too much, the visual representation can be counterproductive and, thus, the IC should be kept simple (Kabisch et al. 2014). Moreover, Becker et al. (2014) recognize geographical information systems (GIS) as a valuable participatory instrument for representing and discussing different vulnerability factors or suitable indicators or as a platform for visualizing and monitoring vulnerability results. Two further challenges are that ICs represent conditions at a given time and are thus unable to integrate dynamic feedback loops (Schneiderbauer et al. 2020) and that they are often very context-specific and therefore cannot be generalized to other settings (Kabisch et al. 2014).

4) QUANTIFICATION OF SYSTEM ELEMENTS AND INTERRELATIONS

Most of the challenges associated with quantifying system elements and interrelations found within the articles that focus on quantitative models and simulations.

When the assessments aim to estimate future costs and monetary losses and damages, factors that contribute to risk might be discarded due to insufficient knowledge or data, despite understanding their importance. For example, Steininger et al. (2016) assessed the potential economic impacts of climate change across many sectors in Austria. However, insufficient knowledge of the impact fields of human health and ecosystems/biodiversity resulted in their exclusion from a macroeconomic model. According to them, one reason for these shortcomings is the lack of available researchers specialized in the respective impact fields "who can specify impact chains and develop and apply the respective impact models."

Complexity significantly increases when assessing several interrelated climate change risks or affected sectors simultaneously (Harrison et al. 2016; Terzi et al. 2019). Dawson (2018) explores the handling of interdependencies between climate change risks using a systems approach. In his study, he explains how interactions between climate hazards, physical processes operating over long distances, and shared climatic and nonclimatic drivers can impact risk while stressing that there can be no "one size fits all" approach.

5) DATA GAPS: THEY ARE GETTING BETTER BUT DATA OF THE FUTURE ARE A CHALLENGE

Although the availability and quality of projected climate and hazard scenario data is constantly improving, methodological gaps and uncertainties with regard to the future development of vulnerability and exposure prevail. This is because vulnerability and exposure are not bound to physical laws and follow shorter-term dynamics, which renders them difficult to predict over the long term. The result is that projections for long-term demographic, socioeconomic developments and intersectoral interactions are sometimes neglected in CRVA due to a lack of data (Rome et al. 2019; Schwarze 2015). However, understanding vulnerability and exposure, their interrelations, and how they might develop in the future are key to understanding future climate risk.

One opportunity is the integration of socioeconomic scenarios into the assessment. They provide possible pathways for future developments based on major driving forces and possible impacts (Schweizer and Kurniawan 2016). Twenty-five of the reviewed articles applied climate scenario(s), while 18 applied socioeconomic scenarios, mostly for future exposure conditions. However, while the emerging abundance of climate scenarios, socioeconomic, land-use and demographic scenarios offer new opportunities, Steininger et al. (2016) note the difficulty of choosing the most appropriate among a growing range of scenarios and the difficulty of comparing studies that applied differing scenarios.

Another prevailing bottleneck is the availability of, and access to, reliable data for quantitative CRVA (Becker et al. 2014; Debortoli et al. 2018; Gies et al. 2014). Especially spatially explicit CRVA are challenged by incomplete or inconsistent data, such as heterogeneous spatial scales (Anandhi et al. 2018; Becker et al. 2014), the collection and assembly of high-resolution, national-scale data (Thacker et al. 2018), or denied access (Rome et al. 2019). Consequently, aspects that cannot be captured due to missing data tend to be disregarded despite their integral role in the system (Kienberger et al. 2016), thus limiting the quality and validity of the assessment.

6) LACKING EVALUATION AND VALIDATION OPTIONS: HOW DOES ONE EVALUATE SOMETHING THAT HAS NOT HAPPENED YET?

The limited possibility to evaluate and validate CRVA results is recognized as the main factor hindering the identification and quantification of risk factors and their dynamic cause–effect relationships. Many CRVA results cannot be evaluated or validated (yet) because they aim to estimate the risk level at the middle or end of the twenty-first century. Consequently, a general lack of methods and schemes to evaluate and validate future risks prevails (Becker et al. 2014; Hussain 2014).

The missing impact data is caused by a lack of evaluations of past (economic) impacts, especially for the validation of indirect costs, as "wider economic impacts after a disaster are usually not well documented" (Dottori et al. 2018) or, as Koks et al. (2019) point out for Europe, are "lacking almost completely." This neglect results from the cost and resource intensity of collecting such data and a lack of strategies to quantify indirect impacts (Koks et al. 2019) and factors of nonmonetary value (Thacker et al. 2018). The adverse impacts of biodiversity loss and the impairment of ecosystem services are particularly difficult to estimate since these impacts are both indirect and not meaningfully expressible in monetary terms (Lapola et al. 2018; Schwarze 2015).

With little means to validate CRVA results relating to future risks, several authors warn of the underestimation of future costs and impacts (Lapola et al. 2018; Schweizer and Kurniawan 2016; Sperotto et al. 2019; Thacker et al. 2018; Tsavdaroglou et al. 2018). If true costs tend to be underestimated, they cannot be meaningfully compared with the costs and benefits of adaptation options (Thacker et al. 2018). Another challenge lies in the comparability of assessment results since comparable information is often unavailable, for example, on existing adaptation measures (Tsavdaroglou et al. 2018).

As an opportunity, Tapia et al. (2017) suggest evaluating adaptation measures that are already in practice to build a better evidence base. Furthermore, narrative examples of the connection between risk and vulnerability from historical events can promote an understanding of the linkages between climate risks, which in turn provides a better understanding of a particular risk.

4. Discussion

In this section, we discuss the lessons learned from previous IC applications and whether and how the opportunities identified in the reviewed literature can fill the IC's methodological gaps. The discussion is structured into two sections: section 4a discusses which lessons learned can be used to improve the participatory phase, and section 4b discusses how the operational phase can be improved.

a. *Improving IC's participatory phase*

The articles clustered as qualitative models of cause and effect showed that a range of methods already offer solutions to integrate cause–effect dynamics into IC, such as causal loop diagrams (Olabisi et al. 2018; Tonmoy and El-Zein 2013) or similar approaches, for example, deterministic graphs (Lissner et al. 2012) and fuzzy cognitive maps (Romero-Lankao and Norton 2018). The most common knowledge and information source in the qualitative CRVA were stakeholders and experts. Involving them throughout the whole research process, and keeping them engaged, requires time and commitment (Greiving et al. 2015; Schneiderbauer et al. 2013). However, their involvement offers the opportunity to integrate academic with expert and local knowledge, making the assessment more specific to the given circumstances. On the national and subnational scales, key stakeholders were generally experts from environmental ministries and agencies, statistical offices, meteorological services, universities, and the private sector. While local knowledge enhances context specificity, the involvement of climate risk managers at the institutional level increases the relevance of the results. Involving the latter has the potential to foster their sense of ownership, increase cross-office and cross-department communication, and improve the chances that assessment results are agreed upon and adaptation options built upon them. They are usually also key data providers (Kienberger et al. 2016; Lückerath et al. 2018a; Zebisch et al. 2021).

Nevertheless, when a diverse group discusses a complex impact chain and risk factors, there is potential for disagreements. The participants may differ in objectives and worldview: for example, participants from private companies might have opposing objectives from one another and from participants from the public sector. When we aim to move from linear and sectoral impact chains to complex webs of cause–effect relationships among risk factors, the accompanying discussions are expected to become substantially more challenging. This bears even more potential to reveal conflicting perspectives on the same system. However, considering cause–effect dynamics in the IC is a valuable opportunity to stimulate discussions (although they may not be easy) and shape or enhance everyone's understanding of the dynamic dimension of risk. In the best case, this deepens the participants' understanding of which IC parts they consider most relevant and locate effective entry points for adaptation measures. We, therefore, suggest keeping detailed documentation of the discussion process to limit the potential for conflicts and consider the discussion as a learning process and intermediate outcome in itself.

While some stakeholders will have experienced climate impact related problems already, others might not have. So, the individual risk perceptions might be skewed based on past experiences or a lack of past experiences. Thus, potential biases and insufficient experience/knowledge to clearly determine cause and effect relationships must be considered and compensated for.

To facilitate a fruitful discussion in which key drivers of risks and their interrelations are successfully identified, a focused assessment preparation (scoping) phase is required, where the subject is thoroughly explored and delineated. This functions as the basis of all further discussions to ensure that all involved parties understand the objectives and context. While objectives and context should be clearly delineated and communicated, we suggest placing less emphasis on concepts and frameworks (such as vulnerability, sensitivity etc.). While a common set of terms and definitions can be beneficial, it should be adjusted to the participants' backgrounds so as not to overwhelm or confuse them. Adding conceptual terms to the IC after the IC elements have been determined and arranged may allow the participants to better understand sensitivities, critical states, and weak elements in the system and identify entry points for sustainable adaptation.

When discussing and documenting risk contribution factors and their interrelationships, illustrations of the system can quickly become crowded. Splitting the system into subcategories could reestablish clarity (Kabisch et al. 2014; Yokohata et al. 2019).

Opinions authors and experts vary on whether the risk should be discussed and assessed for one sector/affected community at a time or whether this makes results prone to misrepresentation. Previous IC applications suggest keeping the discussions in stakeholder workshops focused on one IC at a time. Each IC's cross-sectoral interconnections in a larger context should be acknowledged in subsequent analysis steps.

b. *Improving IC's operational phase*

Plenty of dynamics-focused CRVA have successfully managed to quantify and connect the risk components in executable models under different scenarios. However, data availability problems and the uncertainty about the future development of highly dynamic dimensions, such as vulnerability and exposure, prevail. Data availability problems affect geographic and indirect impact data in particular. This lack can, to some extent, be compensated for through the involvement of local experts and stakeholders who can provide insights into local processes and often have access to data that would otherwise not be accessible to the researchers. Therefore, possible constraints on the availability of local data and data-sharing policies should be anticipated, and the role of the stakeholders as possible data providers should be discussed early in the process. Other important data providers are international and national open access repositories, statistical yearbooks, and publicly available GIS systems for spatial data.

Furthermore, there are gaps in the availability of data on comparable, subnational, future projections of vulnerability and exposure factors. While projected data for future climate trends is widely available (e.g., Giorgi et al. 2009; Taylor et al. 2012), vulnerability and exposure dimensions might be as dynamic, or even significantly more dynamic, than climate. For instance, the accumulation of assets and values in floodplains might increase the risk related to flood damage as much, or even more, than an increase in floods. In those cases, it must be evaluated whether a quantitative assessment would yield meaningful results or whether an exclusively expert-based assessment would be more appropriate. However, this challenge is widely acknowledged in the community and has led to the development of a range of socioeconomic scenarios, for example, the shared socioeconomic pathways (Nakicenovic et al. 2014; O'Neill et al. 2017, 2014).

Current approaches usually utilize IC as the backbone for static, linear representations of risk, primarily through composite indicator approaches. System dynamics models and related approaches provide an opportunity to link the IC approach with system-based modeling. This is particularly useful for more in-depth and scientific assessments.

Moving the IC method from a static, indicator-based representation of risk toward a more system dynamics-oriented approach requires an even better understanding of the systemic relationships, more data, more time, even deeper integration of stakeholders, and clear communication of limitations and uncertainties. Quantifying cause–effect relationships and projecting future developments entails uncertainties, especially with limited possibilities to evaluate and validate results. Thus, uncertainties and confidence levels should be addressed in each assessment step.

However, moving from static risk models to dynamic quantifications and executable models that integrate feedback is a very promising approach, as risk, by nature, is a dynamic phenomenon, and a more precise representation of it will lead to more informed decisions that enable a sustainable adaptation policy.

5. Conclusions

Using the available literature, we reviewed and summarized the current state of the art of IC and similar CRVA methods. The IC method is already perceived as a helpful tool to understand and communicate risk processes and offers a range of opportunities for integrating more features that enable the integration of dynamic and causal structures. Innovative key features are its participatory nature, its integral position within CRVA, and the possibilities of incorporating systemic thinking. The combination of quantitative information and literature-based information with expert judgements and/or stakeholder participation is generally perceived as the best practice.

There are several reasons for the strong positive perception of stakeholder involvement in CRVA, such as the added context and place specificity they can offer, and the fact that their experience can significantly contribute to the validation of results. However, potential biases could impair the representativeness of the results and must be kept in mind and, if necessary, be compensated for. Involving stakeholders throughout the entire assessment process fosters their sense of ownership and confidence in the results, resulting in the increased likelihood of advice on adaptation options to be put into action. Through their consistent involvement in the scientific process, limitations, and uncertainties in the data and methods, but also strengths and certainties are made transparent, enabling them to understand the extent of the results' meaning and significance. Engaging stakeholders to exploit synergies of knowledge, experience, and data will be the key to future improvements of assessment results, and their involvement is also critical to sparking tangible action in adaptation planning.

We find that linear, sectoral representations of risk factors in classical impact chains could be turned into cause–effect impact webs through already existing methods, such as causal loop diagrams. However, the cause–effect impact webs that ICs are supposed to depict are usually complex and not yet fully understood. Thus, it must be kept in mind that the IC do not necessarily represent reality but rather participants' understanding of reality. Turning stakeholder- and expert-generated IC into quantifiable, executable models bears potential. However, it is highly underexplored and challenging because of the often limited system understanding and available data. Whether a data-driven assessment would yield useful information can therefore vary.

The conceptual framework on which the IC method is based is useful to make assessment results comparable. However, it is also bulky and sometimes challenging for users and stakeholders to understand and follow discussions that are too heavily laden with jargon. We found that, for example, the use of a standardized concept of risk, as proposed in the IPCC AR4 or AR5, is still not operationalized or acknowledged in every assessment. This means that different approaches and results are not necessarily comparable. This divergent development could also entail lacking synergies and misuse of resources.

Future developments should further work on integrating quantitative, semiquantitative, qualitative, and narrative approaches to create a bigger picture of the risk system of interest. Moreover, a stronger link between IC development and the identification of adaptation options should be established. Building on that, discussions about different sustainable adaptation pathways could become an integral part of the participatory IC development process. In the effort to develop sustainable adaptation pathways, not only the challenge of overall sustainability can be addressed, but also a variety of different SDG targets given the multidimensional and multifaceted nature of the risk concept.

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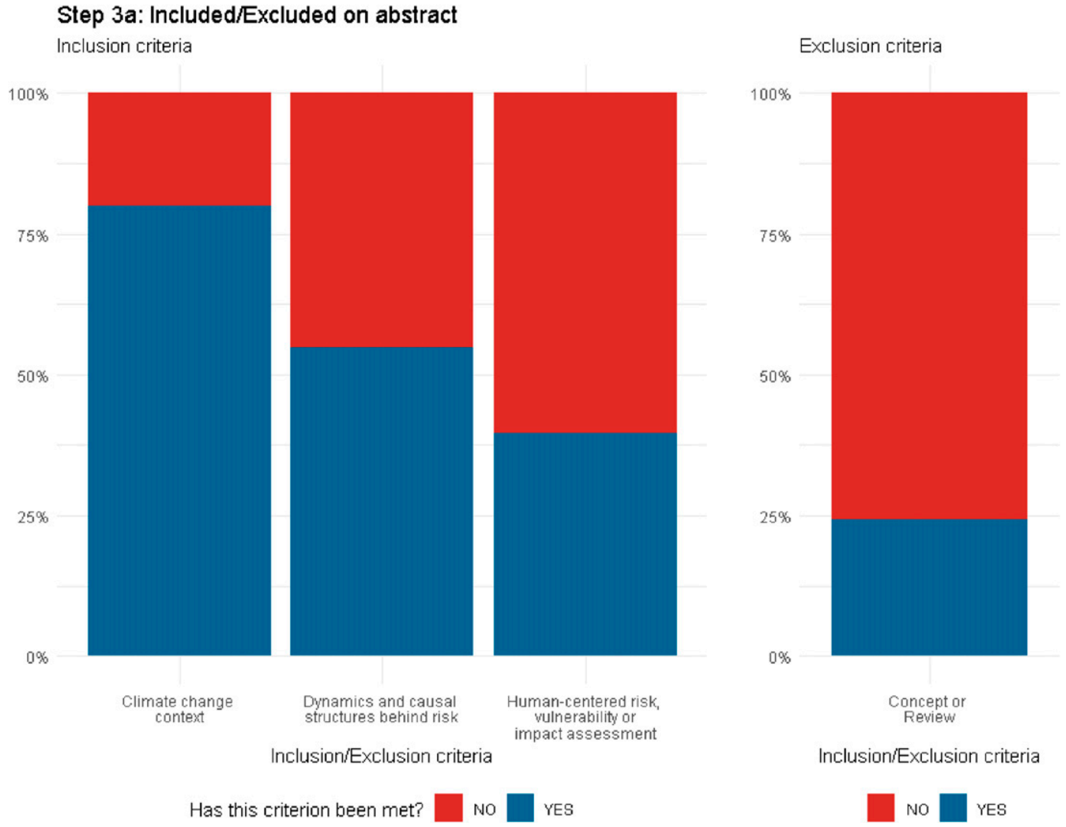

FIG. A1. The percentage of abstracts that matched each inclusion/exclusion criterion. The figure relates to step 3a of the review process shown in Figs. 3 and 4. More than 75% of all abstracts could be linked to a climate change context. About 50% were focused on the dynamics and causal structures governing risk. Only less than one-half of them were human-centered risk, vulnerability, or impact assessments. *Human-centered* means that we excluded assessments that exclusively focused, e.g., on animal or plant populations. About 25% were excluded because they were purely conceptual or review papers.

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Data availability statement. The datasets generated during and/or analyzed during the current study are available in the IC-review supplementary repository (https://github.com/Menkli/IC_review_supplementary).

APPENDIX

Detailed Overview of the Selection Decisions

Figure A1 reports the percentage of abstracts that matched each inclusion/exclusion criterion and relates to step 3a of Figs. 3 and 4.

REFERENCES

Anandhi, A., A. Sharma, and S. Sylvester, 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**, e1997, https://doi.org/10.1002/eco.1997.

Becker, D., K. Renner, and S. Schneiderbauer, 2014: Assessing and mapping climate change vulnerability with the help of GIS: Example of Burundi. *GI_Forum 2014*, Salzburg, Austria, Geospatial Innovation for Society, 101–104, http://austriaca.at/0xc1aa5576_0x0030d408.pdf.

Berkes, F., C. Folke, and J. Colding, 2000: *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.* Cambridge University Press, 459 pp.

Bierkandt, R., L. Wenz, S. N. Willner, and A. Levermann, 2014: Acclimate—A model for economic damage propagation. Part 1: Basic formulation of damage transfer within a global supply network and damage conserving dynamics. *Environ. Syst. Decis.*, **34**, 507–524, https://doi.org/10.1007/s10669-014-9523-4.

Birkmann, J., and Coauthors, 2013: Framing vulnerability, risk and societal responses: The MOVE framework. *Nat. Hazards*, **67**, 193–211, https://doi.org/10.1007/s11069-013-0558-5.

Buth, M., W. Kahlenborn, S. Greiving, M. Fleischhauer, M. Zebisch, S. Schneiderbauer, and I. Schauser, 2017: Leitfaden für Klimawirkungs-und Vulnerabilitätsanalysen (Guidelines for climate impact and vulnerability analyses). Umweltbundesamt Rep., 48 pp., https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/uba_2017_leitfaden_klimawirkungs_und_vulnerabilitatsanalysen.pdf.

Caniglia, B., B. Frank, B. Kerner, and T. L. Mix, 2016: Water policy and governance networks: A pathway to enhance resilience toward climate change. *Sociol. Forum*, **31**, 828–845, https://doi.org/10.1111/socf.12275.

Crichton, D., 1999: The risk triangle. *Natural Disaster Management*, J. Ingleton, Ed., Tudor Rose, 102–103.

Dawkins, E., K. André, K. Axelsson, L. Benoist, Å. G. Swartling, and Å. Persson, 2019: Advancing sustainable consumption at the local government level: A literature review. *J. Cleaner Prod.*, **231**, 1450–1462, https://doi.org/10.1016/j.jclepro.2019.05.176.

Dawson, R. J., and Coauthors, 2018: A systems framework for national assessment of climate risks to infrastructure. *Philos. Trans. Roy. Soc.*, **A376**, 20170298, https://doi.org/10.1098/rsta.2017.0298.

Daze, A., K. Ambrose, and C. Ehrhart, 2009: *Climate Vulnerability and Capacity Analysis Handbook.* Care International, 77 pp., https://careclimatechange.org/wp-content/uploads/2016/06/CARE-CVCA-Handbook-EN-v0.8-web.pdf.

Debortoli, N. S., J. S. Sayles, D. G. Clark, and J. D. Ford, 2018: A systems network approach for climate change vulnerability assessment. *Environ. Res. Lett.*, **13**, 104019, https://doi.org/10.1088/1748-9326/aae24a.

Dikanski, H., A. Hagen-Zanker, B. Imam, and K. Avery, 2016: Climate change impacts on railway structures: Bridge scour. *Proc. Inst. Civ. Eng. Eng. Sustainability*, **170**, 237–248, https://doi.org/10.1680/jensu.15.00021.

Dilling, L., M. E. Daly, W. R. Travis, O. V. Wilhelmi, and R. A. Klein, 2015: The dynamics of vulnerability: Why adapting to climate variability will not always prepare us for climate change. *Wiley Interdiscip. Rev.: Climate Change*, **6**, 413–425, https://doi.org/10.1002/wcc.341.

Distefano, T., M. Riccaboni, and G. Marin, 2018: Systemic risk in the global water input-output network. *Water Resour. Econ.*, **23**, 28–52, https://doi.org/10.1016/j.wre.2018.01.004.

Dottori, F., and Coauthors, 2018: Increased human and economic losses from river flooding with anthropogenic warming. *Nat. Climate Change*, **8**, 781–786, https://doi.org/10.1038/s41558-018-0257-z.

Espada, R. J., Apan, A., and K. McDougall, 2015: Vulnerability assessment and interdependency analysis of critical infrastructures for climate adaptation and flood mitigation. *Int. J. Disaster Resilience Built Environ.*, **6**, 313–346, https://doi.org/10.1108/IJDRBE-02-2014-0019.

Evans, B., and Coauthors, 2018: Mapping urban infrastructure interdependencies and fuzzy risks. *Procedia Eng.*, **212**, 816–823, https://doi.org/10.1016/j.proeng.2018.01.105.

Fluixá-Sanmartín, J., A. Morales-Torres, I. Escuder-Bueno, and J. Paredes-Arquiola, 2019: Quantification of climate change impact on dam failure risk under hydrological scenarios: A case study from a Spanish dam. *Nat. Hazards Earth Syst. Sci.*, **19**, 2117–2139, https://doi.org/10.5194/nhess-19-2117-2019.

Ford, J. D., T. Pearce, G. McDowell, L. Berrang-Ford, J. S. Sayles, and E. Belfer, 2018: Vulnerability and its discontents: The past, present, and future of climate change vulnerability research. *Climatic Change*, **151**, 189–203, https://doi.org/10.1007/s10584-018-2304-1.

Fritzsche, K., S. Schneiderbauer, P. Bubeck, S. Kienberger, M. Buth, M. Zebisch, and W. Kahlenborn, 2014: The Vulnerability Sourcebook: Concept and guidelines for standardised vulnerability assessments. Deutsche Gesellschaft für Internationale Zusammenarbeit Rep., 180 pp., https://www.adaptationcommunity.net/download/va/vulnerability-guides-manuals-reports/vuln_source_2017_EN.pdf.

Gies, L., D. B. Agusdinata, and V. Merwade, 2014: Drought adaptation policy development and assessment in East Africa using hydrologic and system dynamics modeling. *Nat. Hazards*, **74**, 789–813, https://doi.org/10.1007/s11069-014-1216-2.

Giorgi, F., C. Jones, and G. R. Asrar, 2009: Addressing climate information needs at the regional level: The CORDEX framework. *WMO Bull.*, **58**, 175–183.

Greiving, S., and Coauthors, 2015: A consensus based vulnerability assessment to climate change in Germany. *Int. J. Climate Change Strategies Manage.*, **7**, 306–326, https://doi.org/10.1108/IJCCSM-11-2013-0124.

Haddaway, N., P. Woodcock, B. Macura, and A. Collins, 2015: Making literature reviews more reliable through application of lessons from systematic reviews. *Conserv. Biol.*, **29**, 1596–1605, https://doi.org/10.1111/cobi.12541.

Hagenlocher, M., S. Schneiderbauer, Z. Sebesvari, M. Bertram, K. Renner, F. Renaud, H. Wiley, and M. Zebisch, 2018: Climate risk assessment for ecosystem-based adaptation: A guidebook for planners and practitioners. Deutsche Gesellschaft für Internationale Zusammenarbeit Rep., 120 pp., https://www.adaptationcommunity.net/wp-content/uploads/2018/06/giz-eurac-unu-2018-en-guidebook-climate-risk-asessment-eba.pdf.

Harrison, P. A., R. W. Dunford, I. P. Holman, and M. D. Rounsevell, 2016: Climate change impact modelling needs to include cross-sectoral interactions. *Nat. Climate Change*, **6**, 885–890, https://doi.org/10.1038/nclimate3039.

Hedlund, J., S. Fick, H. Carlsen, and M. Benzie, 2018: Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk. *Global Environ. Change*, **52**, 75–85, https://doi.org/10.1016/j.gloenvcha.2018.04.006.

Hedrich, M., M. Eller, and A. Sonnenburg, 2016: A methodological framework for sustainability risks identification in the urban water sector. *Int. J. Saf. Secur. Eng.*, **6**, 321–329, https://doi.org/10.2495/SAFE-V6-N2-321-329.

Huq, I., Y. Anokhin, J. Carmin, D. Goudou, F. Lansigan, B. Osman-Elasha, and A. Villamizar, 2014: Adaptation needs and options. *Structure*, **14**, 833–868, https://doi.org/10.1017/CBO9781107415379.019.

Hussain, S. S., 2014: Adapting to climate change: A new tool for communities. *Appropriate Technol.*, **41**, 36–40.

International Organization for Standardization, 2019: Adaptation to climate change—Guidelines on vulnerability, impacts and risk assessment. ISO 14091:2021, 39 pp., https://www.iso.org/standard/68508.html.

IPCC, 2001: *Climate Change 2001: Impacts, Adaptation, and Vulnerability.* J. J. McCarthy et al., Eds., Cambridge University Press, 1042 pp., https://www.ipcc.ch/site/assets/uploads/2018/03/WGII_TAR_full_report-2.pdf.

——, 2007: *Climate Change 2007: Impacts, Adaptation and Vulnerability.* M. L. Parry et al., Eds., Cambridge University Press, 976 pp., https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf.

——, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* C. B. Field et al., Eds., Cambridge University Press, 582 pp., https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf.

——, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects.* V. R. Barros et al., Eds., Cambridge University Press, 688 pp., https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartB_FINAL.pdf.

Jurgilevich, A., A. Räsänen, F. Groundstroem, and S. Juhola, 2017: A systematic review of dynamics in climate risk and vulnerability assessments. *Environ. Res. Lett.*, **12**, 013002, https://doi.org/10.1088/1748-9326/aa5508.

Kabisch, S., R. Chakrabarti, T. Wolf, W. Kiewitt, T. Gorman, A. Chaturvedi, and R. Arora, 2014: Climate change impact chains in the water sector: Observations from projects on the East India coast. *J. Water Climate Change*, **5**, 216–232, https://doi.org/10.2166/wcc.2013.118.

Kang, Y., and C.-S. Park, 2018: A multi-risk approach to climate change adaptation, based on an analysis of South Korean newspaper articles. *Sustainability*, **10**, 1596, https://doi.org/10.3390/su10051596.

Kelly, R. A., and Coauthors, 2013: Selecting among five common modelling approaches for integrated environmental assessment and management. *Environ. Modell. Software*, **47**, 159–181, https://doi.org/10.1016/j.envsoft.2013.05.005.

Kienberger, S., M. Borderon, C. Bollin, and B. Jell, 2016: Climate change vulnerability assessment in Mauritania: Reflections on data quality, spatial scales, aggregation and visualizations. *GI_Forum*, **1**, 167–175, https://doi.org/10.1553/giscience2016_01_s167.

Koks, E., M. Thissen, L. Alfieri, H. De Moel, L. Feyen, B. Jongman, and J. Aerts, 2019: The macroeconomic impacts of future river flooding in Europe. *Environ. Res. Lett.*, **14**, 084042, https://doi.org/10.1088/1748-9326/ab3306.

Landauer, M., S. Juhola, and M. Söderholm, 2015: Inter-relationships between adaptation and mitigation: A systematic literature review. *Climatic Change*, **131**, 505–517, https://doi.org/10.1007/s10584-015-1395-1.

Lapola, D. M., and Coauthors, 2018: Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. *Proc. Natl. Acad. Sci. USA*, **115**, 11 671–11 679, https://doi.org/10.1073/pnas.1721770115.

Lissner, T. K., A. Holsten, C. Walther, and J. P. Kropp, 2012: Towards sectoral and standardised vulnerability assessments: The example of heatwave impacts on human health. *Climatic Change*, **112**, 687–708, https://doi.org/10.1007/s10584-011-0231-5.

Lomba-Fernández, C., J. Hernantes, and L. Labaka, 2019: Guide for climate-resilient cities: An urban critical infrastructures approach. *Sustainability*, **11**, 4727, https://doi.org/10.3390/su11174727.

Lozoya, J., and Coauthors, 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*, Springer, 373–399.

Lückerath, D., M. Bogen, E. Rome, B. Sojeva, O. Ullrich, R. Worst, and J. Xie, 2018: The RESIN climate change adaptation project and its simple modeling approach for risk-oriented vulnerability assessment. *Simul. Notes Europe*, **28**, 49–54, https://www.sne-journal.org/fileadmin/user_upload_sne/SNE_Issues_OA/SNE_28_2/articles/sne.28.2.10412.pn.OA.pdf.

Moglia, M., M. Nguyen, L. Neumann, S. Cook, and T. Nguyen, 2013: Integrated assessment of water management strategies: Framework and case study. *20th Int. Congress on Modelling and Simulation*, Adelaide, SA, Australia, Modelling and Simulation Society of Australia and New Zealand, 2262–2268.

Morchain, D., and H. Robrecht, 2012: Background paper for the Council of Europe's report on resilient cities: 26 January 2012—Final draft. ICLEI—Local Governments for Sustainability, European Secretariat Doc., https://rm.coe.int/1680719be7.

Nakicenovic, N., R. J. Lempert, and A. C. Janetos, 2014: A framework for the development of new socio-economic scenarios for climate change research: Introductory essay. *Climatic Change*, **122**, 351–361, https://doi.org/10.1007/s10584-013-0982-2.

Olabisi, L. S., S. Liverpool-Tasie, L. Rivers III, A. Ligmann-Zielinska, J. Du, R. Denny, S. Marquart-Pyatt, and A. Sidibé, 2018: Using participatory modeling processes to identify sources of climate risk in West Africa. *Environ. Syst. Decis.*, **38**, 23–32, https://doi.org/10.1007/s10669-017-9653-6.

O'Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. van Vuuren, 2014: A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, **122**, 387–400, https://doi.org/10.1007/s10584-013-0905-2.

——, and Coauthors, 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environ. Change*, **42**, 169–180, https://doi.org/10.1016/j.gloenvcha.2015.01.004.

Ouyang, M., 2014: Review on modeling and simulation of interdependent critical infrastructure systems. *Reliab. Eng. Syst. Saf.*, **121**, 43–60, https://doi.org/10.1016/j.ress.2013.06.040.

Pant, R., J. W. Hall, and S. P. Blainey, 2016: Vulnerability assessment framework for interdependent critical infrastructures: Case-study for Great Britain's rail network. *Eur. J. Transp. Infrastruct. Res.*, **16**, https://doi.org/10.18757/ejtir.2016.16.1.3120.

Reilly, J., and Coauthors, 2013: Valuing climate impacts in integrated assessment models: The MIT IGSM. *Climatic Change*, **117**, 561–573, https://doi.org/10.1007/s10584-012-0635-x.

Rome, E., O. Ullrich, D. Lückerath, R. Worst, J. Xie, and M. Bogen, 2018: IVAVIA: Impact and vulnerability analysis of vital infrastructures and built-up areas. *Critical Information Infrastructures Security*, E. Luiijf, I. Žutautaitė, and B. Hämmerli, Eds., Lecture Notes in Computer Science, Vol. 11260, Springer, 84–97, https://doi.org/10.1007/978-3-030-05849-4_7.

——, and Coauthors, 2019: Risk-based analysis of the vulnerability of urban infrastructure to the consequences of climate change. *Critical Infrastructure Security and Resilience: Theories, Methods, Tools and Technologies*, D. Gritzalis, M. Theocharidou, and G. Stergiopoulos, Eds., Advanced Sciences and Technologies for Security Applications, Springer, 55–75, https://doi.org/10.1007/978-3-030-00024-0_4.

Romero-Lankao, P., and R. Norton, 2018: Interdependencies and risk to people and critical food, energy, and water systems: 2013 flood, Boulder, Colorado, USA. *Earth's Future*, **6**, 1616–1629, https://doi.org/10.1029/2018EF000984.

Schneiderbauer, S., L. Pedoth, D. Zhang, and M. Zebisch, 2013: Assessing adaptive capacity within regional climate change vulnerability studies—An Alpine example. *Nat. Hazards*, **67**, 1059–1073, https://doi.org/10.1007/s11069-011-9919-0.

——, and Coauthors, 2020: Spatial-explicit climate change vulnerability assessments based on impact chains. Findings from a case study in Burundi. *Sustainability*, **12**, 6354, https://doi.org/10.3390/su12166354.

Schwarze, R., 2015: On the state of assessing the risks and opportunities of climate change in Europe and the added value of COIN. *Economic Evaluation of Climate Change Impacts*, K. W. Steininger et al., Eds., Springer, 29–42.

Schweizer, V. J., and J. H. Kurniawan, 2016: Systematically linking qualitative elements of scenarios across levels, scales, and sectors. *Environ. Modell. Software*, **79**, 322–333, https://doi.org/10.1016/j.envsoft.2015.12.014.

Sperotto, A., J. Molina, S. Torresan, A. Critto, M. Pulido-Velazquez, and A. Marcomini, 2019: A Bayesian networks approach for the assessment of climate change impacts on nutrients loading. *Environ. Sci. Policy*, **100**, 21–36, https://doi.org/10.1016/j.envsci.2019.06.004.

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

Tapia, C., and Coauthors, 2017: Profiling urban vulnerabilities to climate change: An indicator-based vulnerability assessment for European cities. *Ecol. Indic.*, **78**, 142–155, https://doi.org/10.1016/j.ecolind.2017.02.040.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1.

Terzi, S., S. Torresan, S. Schneiderbauer, A. Critto, M. Zebisch, and A. Marcomini, 2019: Multi-risk assessment in mountain regions: A review of modelling approaches for climate change adaptation. *J. Environ. Manage.*, **232**, 759–771, https://doi.org/10.1016/j.jenvman.2018.11.100.

Thacker, S., S. Kelly, R. Pant, and J. W. Hall, 2018: Evaluating the benefits of adaptation of critical infrastructures to hydrometeorological risks. *Risk Anal.*, **38**, 134–150, https://doi.org/10.1111/risa.12839.

Tonmoy, F., and A. El-Zein, 2013: Vulnerability of infrastructure to sea level rise: A combined outranking and system-dynamics approach. *Proc. 22nd Conf. on European Safety and Reliability (ESREL-2013)*, Amsterdam, Netherlands, Delft University of Technology, 2407–2414.

Tsavdaroglou, M., S. H. Al-Jibouri, T. Bles, and J. I. Halman, 2018: Proposed methodology for risk analysis of interdependent critical infrastructures to extreme weather events. *Int. J. Crit. Infrastruct. Prot.*, **21**, 57–71, https://doi.org/10.1016/j.ijcip.2018.04.002.

United Nations, 2021: Sustainable Development Goals. https://sdgs.un.org/.

WCED, 1987: Report of the World Commission on Environment and Development: Our common future. United Nations Rep., 300 pp., https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.

Yokohata, T., and Coauthors, 2019: Visualizing the interconnections among climate risks. *Earth's Future*, **7**, 85–100, https://doi.org/10.1029/2018EF000945.

Zebisch, M., S. Schneiderbauer, K. Renner, T. Below, M. Brossmann, W. Ederer, and S. Schwan, 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. Deutsche Gesellschaft für Internationale Zusammenarbeit Rep., 68 pp., https://www.adaptationcommunity.net/wp-content/uploads/2017/10/GIZ-2017_Risk-Supplement-to-the-Vulnerability-Sourcebook.pdf.

——, ——, K. Fritzsche, P. Bubeck, S. Kienberger, W. Kahlenborn, S. Schwan, and T. Below, 2021: The vulnerability sourcebook and climate impact chains—A standardised framework for a climate vulnerability and risk assessment. *Int. J. Climate Change Strategies Manage.*, **13**, 35–59, https://doi.org/10.1108/IJCCSM-07-2019-0042.