

ADVANCED REVIEW

Adaptation to transboundary climate risks in trade: Investigating actors and strategies for an emerging challenge

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Abstract

There is growing recognition that international trade can transmit climate risks across borders, requiring new forms of and approaches to adaptation. This advanced review synthesizes knowledge on how, by whom and where adaptation actions can be taken in the agriculture and industrial sectors to reduce these transboundary climate risks (TCRs). We find a material difference in the literature on TCRs in agriculture as compared with industrial sectors. Operational and market risks, in particular reductions in food availability, dominate in agriculture, while supply chain and trade-related risks are highlighted for industry. While the origin of the risk (source) is the primary target of adaptation to agricultural TCRs, the general governance structure, such as UNFCCC and WTO deliberations, are important targets in both sectors. Adaptation at the country of destination and along the trade network is of minor importance in both sectors. Regarding the type of adaptation option, agriculture heavily relies on trade policy, agricultural adaptation, and adaptation planning and coordination, while in industry knowledge creation, research and development, and risk management are seen as essential. Governments and the international community are identified as key actors, complemented by businesses and research as critical players in industry. Some measures, such as protectionist trade policies and irrigation, are controversial as they shift risks across countries and sectors, rather than reduce them. While more research is needed, this review shows that a critical mass of evidence on adaptation to TCRs is beginning to emerge, particularly underscoring the importance of international coordination mechanisms.

This article is categorized under:

- Vulnerability and Adaptation to Climate Change > Institutions for Adaptation
- Vulnerability and Adaptation to Climate Change > Multilevel and Transnational Climate Change Governance

KEYWORDS

adaptation, agriculture, industry, trade, transboundary climate risk

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1 | INTRODUCTION

In a globalizing world, climate risks can often propagate across borders, including through shared watercourses, financial flows, the movement of people, and via international trade (Carter et al., 2021; Hedlund et al., 2018). This emerging phenomenon raises important questions for the climate policy community about the adaptation options that exist to manage these risks, which options are most effective, and who is responsible for implementing them. While trans-boundary climate risks (TCRs) were highlighted as a key gap in the second US National Climate Assessment (Liverman, 2016) and the European Adaptation Strategy (European Commission, 2018), and are receiving significant attention in the upcoming IPCC AR6, no systematic review yet exists which assesses the state of knowledge in this area or provides a comprehensive look at adaptation efforts to respond.

In the last decade, a substantial internationalization of supply chains has occurred due to multilateral trade agreements, lower trade tariffs and investment barriers, declining transport costs, technological advances in information and communication systems, as well as internationalization of R&D activities (Potrafke, 2014; World Bank, 2020). Considering these developments, there is a growing potential for supply chain disruption due to global climate change impacts, as well as low visibility for many firms of second-tier or third-tier suppliers on whom they depend that may be at risk. Existing national risk assessments of European countries agree that the potential costs of climate impacts originating outside Europe can exceed the potential damage from climate impacts originating within Europe (Challinor et al., 2016; 2017; Committee on Climate Change & China Expert Panel on Climate Change, 2018; Leitner et al., 2020; PricewaterhouseCoopers, 2013; UK Foresight, 2011). Yet, despite the recognition of TCRs as a potentially major risk, few national risk assessments consider adaptation options to reduce them.

In this article, we therefore aim to provide a systematic review of the existing knowledge about adaptation options to TCRs with a particular focus on TCRs transmitted through trade. In the last two decades, several TCRs affected trade in agricultural and food products and trade in industry. Examples of the former are the food price crisis of 2008 which was caused by reduced agricultural productivity in several world regions simultaneously (Headey, 2011; Shenggen Fan, 2010) or the 2010 drought and heat wave in Russia which was aggravated by export bans and panic sales on international markets (Challinor et al., 2018; Fellmann et al., 2014). The 2011 Thai floods also disrupted industrial production and transport systems, affecting manufacturing and service sectors at a global scale (Abe, 2014; Gledhill et al., 2013b; Haraguchi & Lall, 2015).

Yet, while TCRs are potentially high both in trade of agriculture/food and of industrial products (Challinor et al., 2016; Surminski et al., 2016), there are also some important differences: agriculture/food products are perishable and storable only a limited time; industrial products have more complex supply chains and are therefore vulnerable to transport disruptions (Ghadge et al., 2020); and this vulnerability may be aggravated by concentration in the supply of critical inputs (Daddi et al., 2020; Nakano, 2017). We therefore assess the knowledge on adaptation to TCRs in trade in these two sectors and discuss differences and communalities.

By conducting a systematic literature review of both the academic and gray literature, we address three specific research questions: (a) Which TCRs are identified as relevant for trade in agricultural products and for supply chains in industry? (b) What are the identified adaptation options to TCRs transmitted through trade and to which extent are potential conflicts of these options discussed? (c) Who are the key actors engaged in managing TCRs (e.g., governments, businesses, international community, non-state actors), and where are the main sites of intervention?

The remainder of this article is structured as follows: Section 2 summarizes the conceptual framework and the methodology of our systematic literature review. In Section 3, we first discuss the emergence of the notion of TCRs in the reviewed literature and then answer our three central research questions. Section 4 discusses the implications of our findings both for research and practitioners. Section 5 concludes with directions for future research.

2 | METHOD

2.1 | Conceptual framework

When discussing adaptation to TCRs in trade, we build and expand on the seminal framework by Smit et al. (2000) who ask three fundamental questions: First, adaptation to what, that is, which climate hazards and TCRs are addressed by adaptation? Second, how is adaptation taking place, for example, distinguishing for different types of adaptation

action? And third, adaptation by whom or which system (e.g., economic sector)? This final question addresses also different scales and sites of adaptation, including governance and the contextual environment.

Regarding the question of adaptation to what, we distinguish between climate hazards and impacts to the sectors (Table 1). For climate hazards, we use the main categories for climatic impact-drivers of the IPCC's 6th Assessment report (IPCC, 2021) and apply this structure to the hazards listed in the Carbon Disclosure Project questionnaire on physical climate risks (see e.g., Goldstein et al., 2019; Sakhel, 2017).

For TCRs in trade, we start from the recommendation of the Task Force to Climate Related Financial Disclosures (TCFD, 2018) that distinguishes three main categories of physical climate risks: operational, market, and supply chain, a structure which was also used in previous reports (e.g., Lühr et al., 2014). For higher granularity within each of the main categories, we screen existing risk classifications for business and industry in general (Goldstein et al., 2019) and expand for the transboundary, and in particular trade, dimension (Carter et al., 2021; Lühr et al., 2014).

For categorization of adaptation options, we started from existing classifications that were used for public institutions and private companies as implementers of adaptation (de Coninck et al., 2018; European Environment Agency, 2013; Goldstein et al., 2019; Noble et al., 2014). As these classifications are, however, primarily used for adaptation within a country or region, we applied inductive coding to refine and adjust these classifications.

Regarding actors, it is important to note that while adaptation is commonly understood as a private good, governments play an important role in the coordination among several actors, as a source of funding (to incentivize proactive actions) and by establishing regulatory frameworks (Bisaro & Hinkel, 2016; Eakin & Patt, 2011; Geaves & Penning-Rowsell, 2016; Tompkins & Eakin, 2012). For TCRs in trade, joint actions by multiple governments such as the European Union or the international community (UNFCCC) are of particular relevance (Leitner et al., 2020). Complementary, the research community can improve the knowledge base on risks and adaptation (Adger et al., 2005; Eakin & Patt, 2011), and also non-state actors such as NGOs can act as knowledge brokers (Ford et al., 2011).

Related to the question of who is adapting to climate change, is where adaptation actions are needed (Adger et al., 2005; Moser & Ekstrom, 2010; Smit et al., 2000). As for adaptation in general, action is needed at various scales (Adger et al., 2005; Biesbroek et al., 2013). But in addition, the question arises whether adaptation action targets the country of origin of the impact (source), the transmission network (path), or the country of final destination (sink) (Carter et al., 2021).

Some have argued that adaptation to TCRs can be classified as an impure public good (Cornes & Sandler, 1996), in that not only the providers benefit from adaptation but benefits also spill over to others (Bisaro & Hinkel, 2016; Roggero et al., 2019). As for any (impure) public good, under-provision of the good is likely in the absence of coordination. We therefore also include “governance” as a potential site of intervention, that is, where adaptation action is facilitated by improving a governance structure or multilateral processes (Persson, 2019). Finally, we also include a fifth category related to knowledge production, which is not necessarily geographically specific.

2.2 | Systematic literature review

We begin our analysis with a comprehensive systematic literature search in SCOPUS. To cover all relevant aspects, our search query consists of four pillars: the type of climate risk (transboundary), the trigger of risk (climate hazard), the pathway of transmission (trade), and the response or strategy to address these risks (adaptation; Figure 1). To assure that all relevant aspects are covered in our results, these four pillars are connected by the search operator “AND.” The terminology used in the relevant literature can vary considerably, and as a result include alternative search terms for each of the four pillars using the search operator “OR.” As research on this topic has been spread across several disciplines, we include literature from geography, economics, political science, climate change adaptation, global environmental governance, and other relevant bodies of work. Additionally, as this research area remains emerging in the peer-reviewed literature, we also complement this body of work with seminal publications in the gray literature, including official reports from governmental, nongovernmental, and research institutions. Details on the search procedure can be found in the Supplementary Material.

After a preliminary screening of all 1032 search results, 163 papers were identified as potentially relevant and screened with greater detail. A total of 56 papers was included in the final sample of peer-reviewed literature alongside 24 pieces of gray literature that were identified by the team of authors based on their collective expertise.

In the course of screening the literature, we find that a large share of papers (61%) consider TCRs in the context of agriculture and food trade, while the remaining literature is distributed across trade in different industrial sectors. A

TABLE 1 Dimensions and categorizations of adaptation to transboundary climate risks in trade

Dimension	Main category	Subcategories and explanation	References
Climate hazard	Heat and Cold	Mean surface temperature Extreme heat	(Goldstein et al., 2019; IPCC, 2021; Sakhel, 2017)
	Wet and Dry	Mean precipitation Heavy precipitation and pluvial flood River flood Landslide Drought (aridity, agricultural, and hydrological drought) Fire	
	Wind	Severe wind storm Tropical cyclone Sand and dust storm	
	Coastal	Relative sea level Coastal flood Extreme weather Not specified	
	Operational risks	Production-based risks (inability to do business; reduced productivity/yields; reduced profitability) Price-related risks (increased operational and capital costs; reduction in capital availability; reduced stock price)	
	Supply chain risks	Supply chain/trade disruption Transport infrastructure disruption	
	Market risks	Macroeconomic damage Availability of goods and services (reduced demand for goods and services; food insecurity) Global systemic risks (global breadbasket failure)	
	Adaptation planning and coordination	National and local adaptation plans and strategies	
	Storage; infrastructure	Storage, infrastructure design and adjustment	
	Trade policy	Trade policy/regulations, including adjustment of trade relations	
	Finance, risk sharing	(International) climate finance, local support, risk sharing instruments (insurance, etc.)	
	Knowledge creation	Awareness-raising, capacity building, knowledge sharing, monitoring, warning, and observing system	
	Research and development	Risk assessment, risk management and planning	
Adaptation to transboundary climate risks in trade	Risk management		(de Coninck et al., 2018; European Environment Agency, 2013; Goldstein et al., 2019; Noble et al., 2014)
	Supply chain management		

TABLE 1 (Continued)

Dimension	Main category	Subcategories and explanation	References
Actors of adaptation	Agricultural adaptation ^a	Farming practices, irrigation, land management	(Carter et al., 2021)
	Agricultural/food policy ^a		
	Government		
	International community	For example, UNFCCC	
	Multiple governments	Bilateral and multilateral arrangements	
	Business		
Sites of adaptation	Research		(Carter et al., 2021; Moser & Hart, 2015; Persson, 2019)
	Non-state actors	NGOs, unions	
	At source	Country, sector, firm where climate risks originates	
	Network/along the pathway	Along the risk transmission pathway (flow of traded goods and services; transport and other infrastructure)	
	At sink	Country, sector, firm where climate risks has its final impact	
	General governance structure	No specific geographical site of adaptation; multilateral processes such as UNFCCC and WTO deliberations	
	Universal knowledge base	No specific geographical site of adaptation; knowledge as global public good	

^aOnly relevant for agriculture.

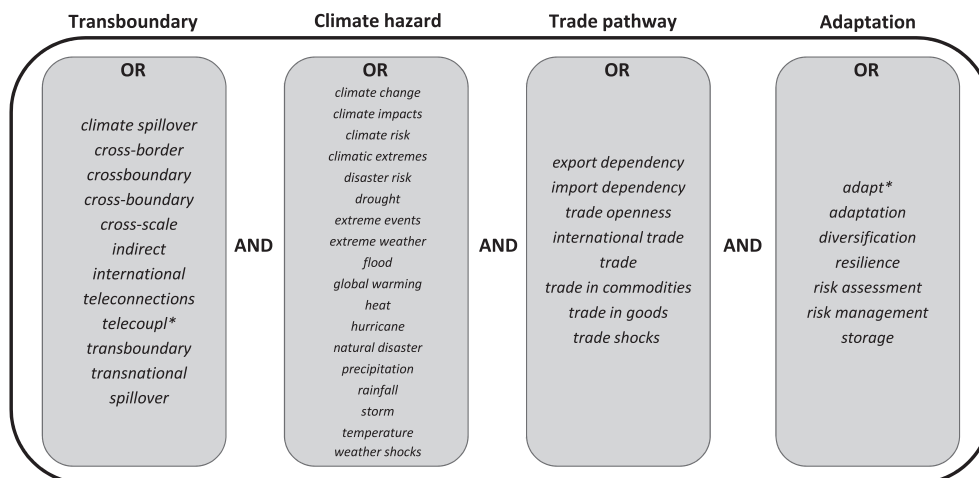


FIGURE 1 Search query for the systematic literature search on SCOPUS

plausible explanation for this focus is that the agricultural sector is directly dependent on weather and climate, whereas industrial sectors are influenced more indirectly via supply chain linkages (Goldstein et al., 2019), resulting in a higher awareness for the need for adaptation in the former sector. In order to determine if substantial differences exist between these two strands of literature, we have divided the literature sample accordingly to facilitate comparison. The agriculture sample includes 40 journal articles, while the industry sample includes 25 journal articles. Nine journal articles were deemed relevant to both the agriculture and industrial sectors and are included in both samples. In addition to journal articles, we also reviewed the gray literature (24 documents in total) and added to each assessment dimension a final paragraph discussing additional aspects raised in this strand of literature.

We then systematically analyzed both samples, reviewing each paper to capture the relevant climate hazard(s) identified, the risks faced by the respective sector, and the adaptation options considered to address these risks, including corresponding key actors and sites of adaptation.

3 | RESULTS

3.1 | The emergence of terminology on trade-related transboundary climate risks

The first observation in our literature review is the different use of terminology related to TCRs. Across the sample, there is a high diversity of terminology used to describe apparently similar phenomena. In order to effectively assess the content of each article, it is critical to understand if these terminological differences are substantive (i.e., reflective of different approaches, concepts, theoretical tools) or a by-product of an emerging field where the collective vocabulary continues to evolve.

The first papers on adaptation to trade-related TCR were published in 2008, and in the period 2011–2015 there was an increase to 3.6 papers per year in the agricultural sample, followed by a comparable increase in the industry sample in the period 2016–2020 (Figure 2a). Figure 2b shows the evolution of terms used in the TCR literature before and after 2015 separated for the agriculture and industry sample. We identified five groups of terminology in our sample, each consisting of several terms with small differences, but still describing the same phenomenon. In Figure 2b, terms belonging to the same group are depicted in the same color.

The first group of papers refers to either “transboundary” or “cross-border” climate risks. In many instances, this literature describes cases where actors share a physical border, including transboundary river basins (Manteaw, 2020; Margulis et al., 2010). Increasingly, however, authors have also begun to broaden the use of this phrase, referring also to climate risks across noncontiguous borders such as those transmitted through trade and supply chains (e.g., Benzie et al., 2019; Challinor et al., 2017; Koks et al., 2019). This category became particularly dominant in the industry sample in the last 5 years (2016–2020; Figure 2b).

The second group of literature relies on a common alternative to the word transboundary: “transnational” or “international” climate risks (e.g., Baldos & Hertel, 2015; Chan & Amling, 2019; Dzebo & Strippel, 2015; Hedlund et al., 2018;

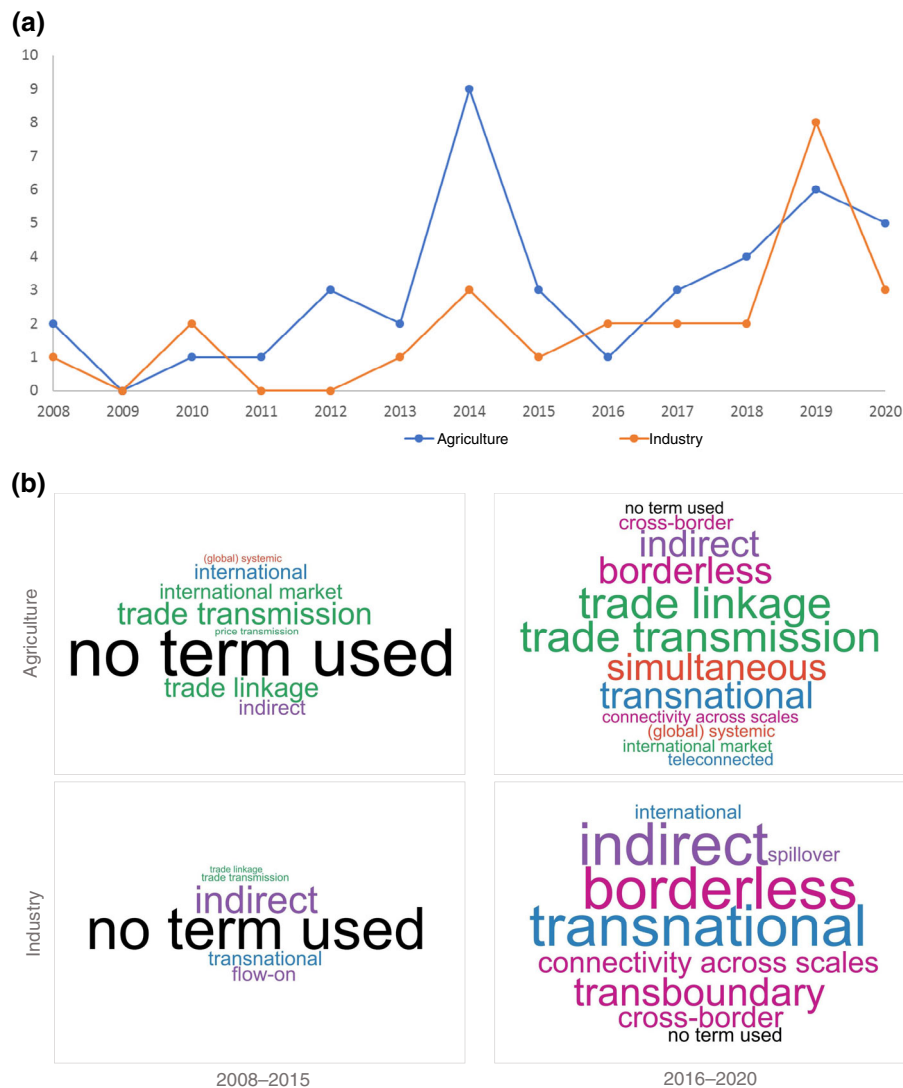


FIGURE 2 Emergence of articles and terminology on trade-related TCRs (a) number of papers published. (b) Word clouds depicting prevalent terminology until 2015 and afterwards. Explanations: The font size in the word clouds reflects the frequency of their usage as the defining term to describe the phenomenon of trade-related TCRs. Similar colors indicate synonymous terms. Frequencies are provided in Table S.1 in the Supplementary Material

Stokeld et al., 2020; Tenggren et al., 2020). While “transboundary” implies a specific focus on the crossing of a border, “transnational” more clearly references the role of the nation state and often invokes the political scientific roots of the term to mean including at least one non-state actor (Risse-Kappen, 1995). Benzie et al. (2017) identified the same dichotomy and conducted a survey of adaptation experts, where respondents were asked how confusing or meaningful various terms were. Survey results suggested that the term “transboundary” was less confusing than “transnational,” but also potentially less accurate. This category has been increasingly used in the last 5 years (2016–2020) in both samples.

A more pronounced distinction exists between the former groups and the third group, which include “cascading” or “indirect” climate risks (e.g., Baldos et al., 2019; Challinor et al., 2017; Constant & Davin, 2019; Hanson & Nicholls, 2020; Lim-Camacho et al., 2017; Mosnier et al., 2014). While the former two groups raise questions about geographical scope and actors, cascading or indirect risk invokes differences between first-order climate risks (e.g., direct climate risks, often contained within national borders) and higher-order risks (e.g., risks which are triggered elsewhere and may flow across sectors or borders). Risks conceptualized in this way may be plausibly contained within a national border, but across sectors, as the key characteristic is the hierarchical ordering of a risk, rather than the distance it flows.

Fourth, and a step further in this direction, another group of papers refers to “systemic” climate risks, in reference to the possibility of interaction effects and feedback loops between risks and systems, rather than a hierarchical structure as cascading risks might suggest (e.g., Gaupp et al., 2020; Puma et al., 2015). While the term “cascading” is more frequently used in the industry sample, the term “systemic” is more frequent in the agriculture sample.

Another group of papers focuses on the transmission system, that is, trade transmission, trade linkage (e.g., Brown et al., 2017; Chen et al., 2012; Janssens et al., 2020; Kummur et al., 2014; Lybbert et al., 2014), while a final group does not use a specific term at all (e.g., Brás et al., 2019; Challinor et al., 2010).

Importantly, the preponderance of each terminological group has changed over time. Up to 2015 more than a third of papers did not use a specific term for TCRs. Many of those papers which did provide a specific term used “price/trade transmission” or “cascading/indirect” climate risks. Since 2016, many papers adopted either the terminology of “transboundary/cross-border” or “transnational/international” climate risks, potentially reflecting a nascent consensus in the scholarly community around these terms. Moreover, the term “systemic” has become more common, particularly in the agriculture sample. Following this trend, our paper adopts the term “transboundary climate risks” (TCRs), which we understand to be inclusive of both systemic climate risks and climate risks transmitted through trade which are less systemic in nature.

3.2 | Adaptation to what: Awareness of hazards and risks

Several climate hazards are mentioned in the reviewed literature as generating TCRs, with on average three hazards identified per paper. Figure 3a shows which climate hazards are mentioned for the two sectors and which TCRs in trade dominate.

In the agriculture sample, 53% of all papers in the peer-reviewed literature identify drought as a relevant climate hazard, as well as increase in average temperature (50% of papers) and increase in heat extremes (43%; Figure 3a). For example, heat and drought are identified as causing crop failure (Ejaz Qureshi et al., 2013; Hertel & Lobell, 2014; Hildén et al., 2020; Huang et al., 2011; Laube et al., 2012; Mosnier et al., 2014) and food supply shocks (Baldos & Hertel, 2015; Brás et al., 2019), as well as leading to increased volatility and spikes in food prices (Benzie & John, 2015; Chatzopoulos et al., 2020; Jerneck & Olsson, 2008; Olawuyi, 2014), and contributing to food insecurity and hunger (Brás et al., 2019; Challinor et al., 2010; Margulis et al., 2010). Flooding and extreme precipitation are mentioned in 38% and 13% of the papers, respectively, as well as sea-level rise (18%) and storms (15%). 20% of papers refer to extreme weather events without specifying the specific type of event.

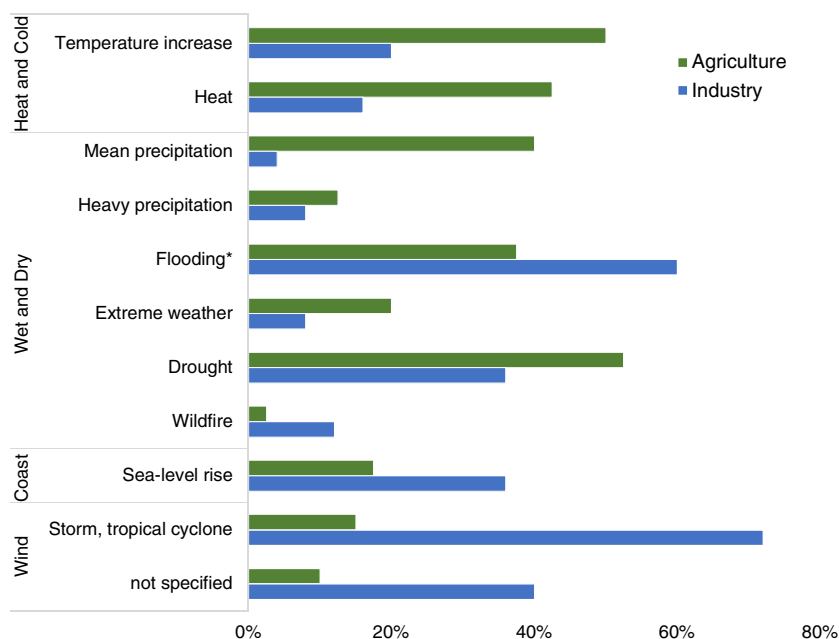
When comparing with the gray literature ($n = 20$ for agriculture), we find overall large agreement on which hazards and risks are most relevant but also a few significant differences. Drought is mentioned most frequently in both the peer reviewed and the gray literature. Yet, all precipitation-related hazards, including flooding and extreme weather, follow directly after drought in the gray literature sample, while these hazards are less prevalent than temperature and heat-related hazards in the peer reviewed sample. This could reveal a bias in the peer reviewed literature because of clearer climate signals in temperature-based indicators compared with precipitation-based indicators.

In the industry sample, similar hazards are mentioned, but distributed differently. Tropical windstorms have a potentially devastating impact on production sites and delivery of goods along the supply chain (Becker et al., 2013; Constant & Davin, 2019; Lei & Wang, 2014; Linnenluecke & Griffiths, 2010; Tenggren et al., 2020), while heat and drought appear to be less important for industrial production as many industrial activities occur indoors. Consequently, storms (72% of papers) and flooding (60%) are mentioned most frequently, followed by sea level rise (36%), drought (36%), increases in average temperature (28%) and extreme heat (16%).

In the gray literature, overall patterns are again similar, but with a few nuances. First, only 6% of the gray literature does not refer to any specific climate hazard while this share is 40% in the peer reviewed literature. Second, extreme weather is mentioned much more frequently in the gray literature (50% compared with 8%), while storm is mentioned much less often (33% compared with 72%). This could be an indication that the gray literature is less accurate in describing the underlying impact drivers (extreme weather as a proxy for storms) but also less hesitant to claim attribution of impacts to climate hazards.

The most prevalent risk for agriculture and food products triggered by these climate hazards are reduction in the availability of agricultural goods (75% of peer reviewed papers, Figure 3b). 50% of papers discuss food insecurity and hunger for developing countries (e.g., Bren D'Amour et al., 2016; Calzadilla et al., 2014); but food supply shocks and food unaffordability are mentioned also as an impact on industrialized countries (Brown, 2018). Production-based risks

(a)



(b)

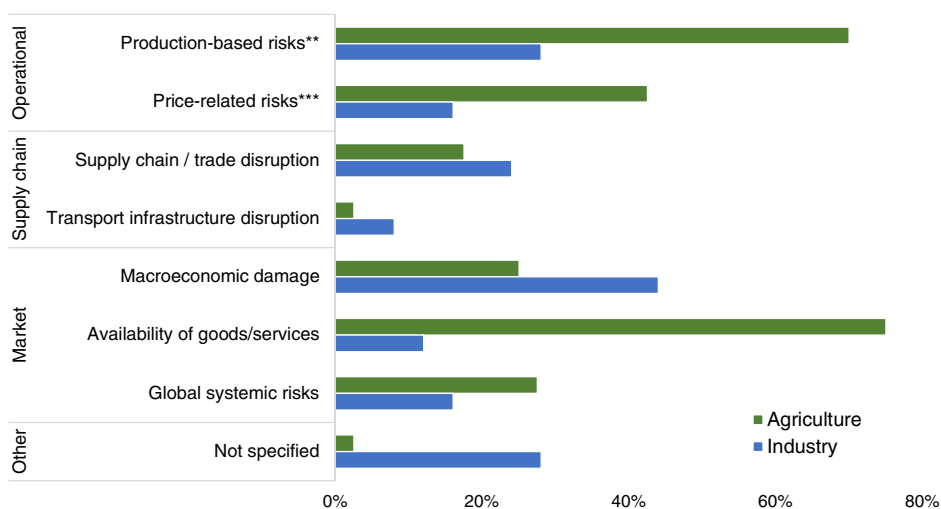


FIGURE 3 (a) Climate hazards and (b) transboundary risks for trade in agriculture and food products and industrial sectors identified in peer-reviewed literature ($n = 40$ for agriculture, $n = 25$ for industry). Explanations: *Riverine and/or coastal flooding; **Business disruption (temporary or permanent), lower productivity (e.g., agricultural yield loss or failure) and profitability (reduced profits); ***Higher prices and/or price volatility of inputs, raw materials; higher output prices. Multiple hazard and risk categories are mentioned per paper; percentages refer to frequency of category relative to number of papers

are mentioned in 70% of papers, referring to agricultural yield loss or failure and yield variability. Price effects, such as higher food prices and price spikes, are mentioned in 43% of papers (Benzie et al., 2019; Jerneck & Olsson, 2008; Magnan et al., 2015; Schenker & Stephan, 2014). 28% of papers highlight global systemic risks, like simultaneous production shocks (Tigchelaar et al., 2018; Villoria & Chen, 2018) and global breadbasket failures (Gaupp et al., 2020). Macroeconomic damage, as well as supply chain/trade disruption are mentioned in 25% and 18% of the papers.

When comparing with the gray literature on agricultural and food products, we find again overall large agreement, but the gray literature focuses more strongly on operational and supply chain risks than on market risks. In particular, price-related risks and supply chain risks are mentioned more than twice as frequently in the gray literature (80% and 61% of papers) while macroeconomic damage is less than half as often discussed (17% of papers).

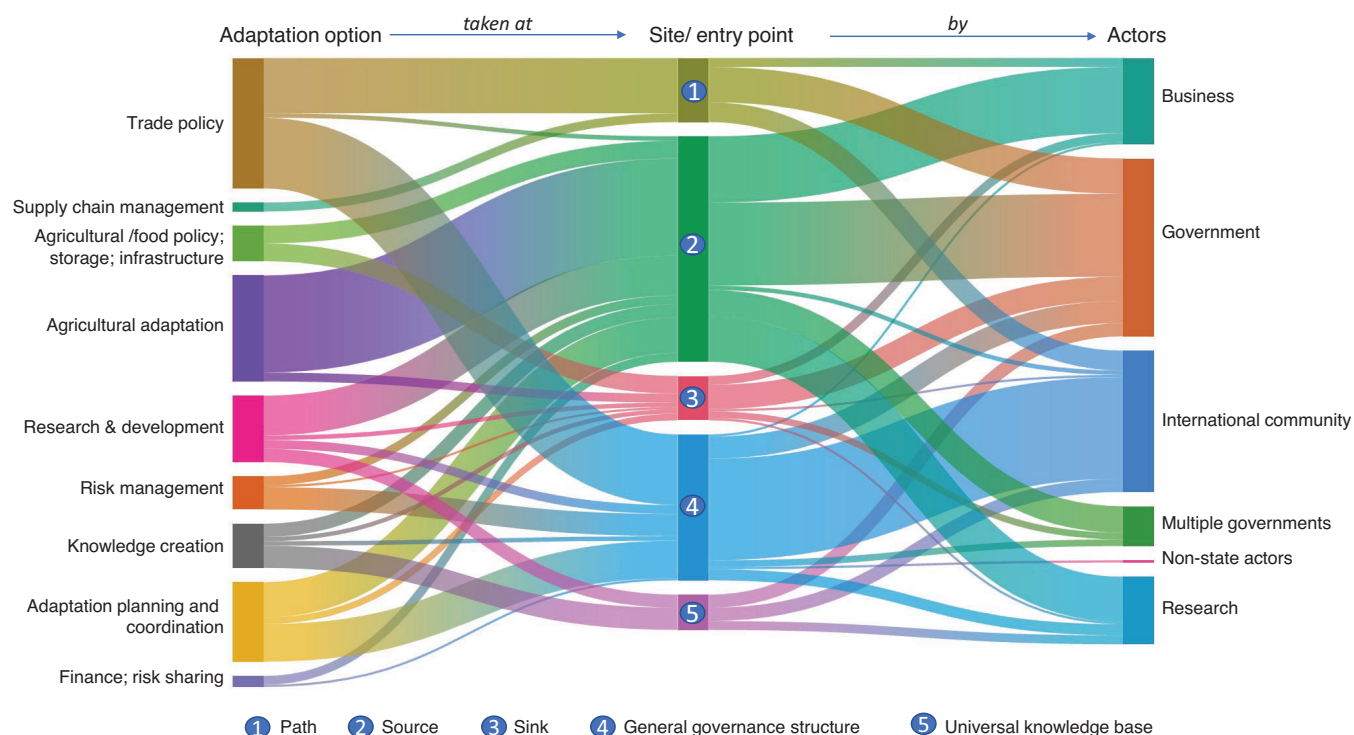


FIGURE 4 Adaptation categories (left), sites (center), and actors (right) to reduce TCRs for trade in agriculture and food products. Flows in the Sankey diagram are based on the number of total nominations of adaptation options ($n = 130$). See Table S.2 in the Supplementary Material for details per paper

For industry, the most cited potential risks are macroeconomic damage and production-based risks (44% and 28% respectively in the peer reviewed literature, Figure 3b), followed by supply chain and trade disruptions (24%). Again, 28% of papers do not specify the type of risk. Sectoral damage here is mainly connected to temporary or permanent business disruption (e.g., Becker et al., 2013; Koks et al., 2019; Linnenluecke & Griffiths, 2010), resulting in lower output and reduced profit margins. Price-related risks and global systemic risks account for 16% each. Transport disruption (e.g., Becker et al., 2013; Hanson & Nicholls, 2020; Peter et al., 2020) accounts for 21%, and the disruption of the availability of goods and services (e.g., Benzie et al., 2019) for 12% of papers.

Yet, in the gray literature on TCRs in industry, supply chain risks constitute the number one risk (61% of papers) followed by price-related risks (44% of papers) and transport disruption (39% compared with 8%) while market risks are again mentioned less frequently in this strand of literature. This perceived higher vulnerability to supply chains and transport networks disruption in the industrial sectors could be explained by more complex value chains compared with agricultural trade.

3.3 | How is adaptation taking place? Options for adaptation to TCRs in trade

3.3.1 | What are the identified adaptation options to TCRs transmitted via trade?

Based on the categorization of adaptation options in Table 1, the left columns of Figures 4 and 5 shows the distribution of adaptation categories and their relative importance for the two literature samples on agriculture and industry (exact numbers can be retrieved from Table 2). The most frequently mentioned category in the agriculture sample is trade policy. This category includes regulatory interventions, such as the elimination or reduction of import tariffs (Chen et al., 2008; Janssens et al., 2020; Ouraich et al., 2019), as well as the adjustment of trade relations as a reactive measure to compensate losses in imports from one place by increased imports from another place. In this context, Lybbert et al. (2014) emphasize the often overlooked feature of trade serving as a buffer for counter-seasonal growing cycles for a given crop shaping intra-annual supply responses. The industry sample, in contrast, has only limitedly explored trade as a potential adaptation option to address TCRs.

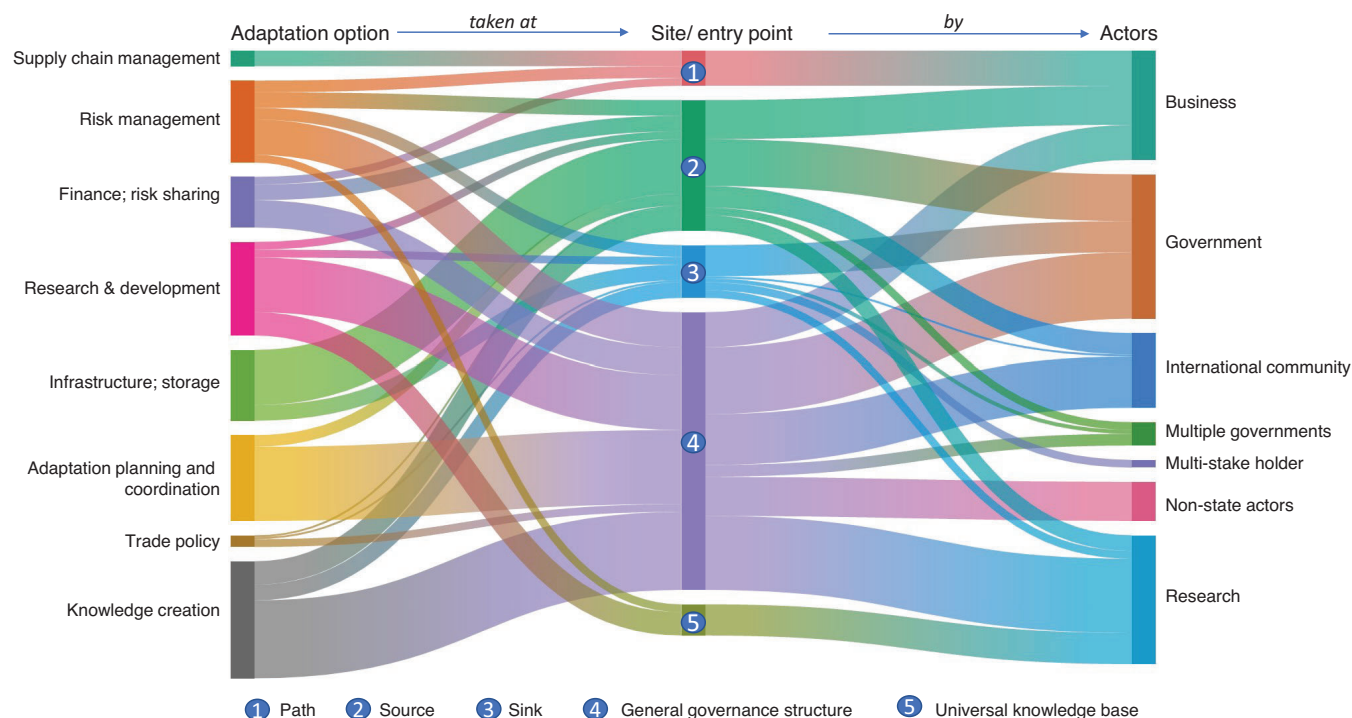


FIGURE 5 Adaptation categories (left), sites (center), and actors (right) to reduce TCRs for trade in industry. Flows in the Sankey diagram are based on the number of total nominations of adaptation options ($n = 81$). See Table S.3 in the Supplementary Material for details per paper

Adaptation planning and coordination are also highly relevant in both literature samples. In the industry sample, Tenggren et al. (2020) for example claim that the management of changing climate-related supply chain risks requires more active dialogue between policy, business and insurance communities, informed by new research. Challinor et al. (2017, p. 623) emphasizes that responses to climate change impacts require “coordination of strategies across policy domains, but also cooperation, trust in evidence, and trust between nations.” Focusing on a case study for seaport infrastructure, Becker et al. (2013) emphasize the need of engaging a comprehensive stakeholder network in planning the resilience of ports. Lei and Wang (2014) argue for a cooperation between climate change adaptation and disaster risk reduction as an essential step toward efficient climate change adaptation. In the agriculture sample, planning/coordination options include the coordination of water markets (Ejaz Qureshi et al., 2013), strategic coordination to build systemic resilience of the food system (Challinor et al., 2017), as well as efficient allocation of resources to contingency plans (Gaupp et al., 2020).

There is also a call for research and development to fill a variety of research gaps that are relevant for climate change adaptation, ranging from projections for regional climatic changes to facilitate local planning (Becker et al., 2013) to the design of global stock-taking methods for adaptation (Persson & Dzebo, 2019). In agriculture, the development of heat-tolerant crops plays a crucial role (Chen et al., 2012).

Knowledge creation is the largest category in the industry sample and fifth largest in agriculture. This category comprises measures of awareness-raising, capacity building, knowledge sharing, monitoring, and warning and observing systems. In the agriculture sample, Calzadilla et al. (2014) and Challinor et al. (2010) reference the importance of better agricultural extension services, while in the industry sample, the focus of knowledge sharing is on the dialogue between different stakeholders (Lei & Wang, 2014; Linnenluecke & Griffiths, 2010). Warning and observing systems are seen as fundamental in the adaptation process to be informed about potential risks and to facilitate timely action (Chatzopoulos et al., 2020; Gaupp et al., 2020). Supporting measures focus on awareness-raising (O’Keeffe et al., 2020; Tenggren et al., 2020) and capacity building (Dzebo & Strippel, 2015) with the aim to enhance adaptation action. Finally, monitoring is a tool that provides information for institutions such as the FAO for intensifying risk monitoring in specific issue areas such as food security (Benzie & Persson, 2019).

Of similar importance to knowledge creation are adaptation options in the risk management category. Many of this option address the assessment of risk as the reduction of vulnerability requires an accurate identification of potential

TABLE 2 Adaptation options identified for agricultural and industrial sectors and their connotation

Sample	Adaptation category	Total number of options	Positive	Neutral	Potential for conflict	Examples
Agriculture	Adaptation planning and coordination	22	14	5	3	Implementing options in isolation (Ejaz Qureshi et al., 2013); negative spillover effects of local adaptation strategies to other regions (Mosnier et al., 2014)
	Agricultural/food policy; storage; infrastructure	8	5	3		
	Trade policy	30	16	2	12	Export bans (Challinor et al., 2017), agricultural tariffs (Janssens et al., 2020), trade restrictions (Kummu et al., 2014), and trade liberalization (Ourach et al., 2019)
	Finance, risk sharing	4	3	1		
	Knowledge creation	11	9	2		
	Research and development	17	13	3		
	Risk management	10	6	2	2	Protectionist policies like the protection of domestic food supply and markets (Puma et al., 2015)
	Supply chain management	4	2	2		
	agricultural adaptation	24	10	12	2	Irrigation impacting water availability (Laube et al., 2012)
	Adaptation planning and coordination	15	11	4		
	infrastructure; storage	9	5	4		
	Trade policy	2		1	1	Policies implemented to protect national interests risk promoting global trade instability (Challinor et al., 2017)
	Finance, risk sharing	8	4	4		
Industry	Knowledge creation	16	10	6		
	Research and development	14	13	1		
	Risk management	13	10	3		
	Supply chain management	4	2	2		

Note: Connotation: positive—an option is (highly) recommended or has proven to have positive impacts (through retrospective studies or modeling); neutral—an option is mentioned in the paper as one option to address certain risks, no evaluation; potential for conflict—an option that is advised against or for which only the adverse effects are discussed, as well as an option for which both characteristics are discussed.

risks and impacts (Becker et al., 2013; O'Keeffe et al., 2020) and complex transmission mechanisms across sectors and borders need to be accounted for in national-level risk assessments (Challinor et al., 2017; Hedlund et al., 2018). Benzie et al. (2019) highlight that existing mechanisms can support risk assessment such as, for example, the EU Civil Protection Mechanism gives a strong competence to the European Commission to address events that can have effects across borders. It includes a national obligation to undertake national risk assessments that consider the potential for cross-border effects (Benzie et al., 2019).

Beyond the assessment of risks, risk management options are relevant to, for example, secure supplies to different crucial products, for instance those used in the construction sector (Koks et al., 2019). This can also be achieved by building up slack resources, such as backup facilities for organizational data and critical systems, access to resource inputs through various suppliers and locations, and financial slack resources (Linnenluecke & Griffiths, 2010). In agriculture, in particular, risk management strategies aim to secure food supply in importing countries by supporting food exporting countries in handling disaster risk (Brás et al., 2019) and by balancing food self-sufficiency and import dependency (Puma et al., 2015).

In contrast to the high importance of supply chains in the context of TCRs and the broader economic benefits of diversified chains, supply chain management is a fairly unexplored adaptation option. Equally relevant for the two samples, Lim-Camacho et al. (2017) emphasize that responses to TCRs can involve the re-partitioning of activity across existing nodes, the introduction of additional nodes and linkages, or the change in the value-added at different nodes through changes in internal processes.

A category that appears to be more prominent in the industry sample than in agriculture is the finance and risk sharing category. The options included are climate finance (Benzie et al., 2019; Constant & Davin, 2019; Schenker & Stephan, 2014) and local support (Jerneck & Olsson, 2008), which are mostly mentioned in the context of developed countries supporting developing countries with climate finance, and risk sharing instruments such as insurance schemes (Koks et al., 2019).

Infrastructure design and adjustment in industrial sectors include measures such as the protection, elevation, or relocation of port facilities (Becker et al., 2013; Hanson & Nicholls, 2020) and other transportation infrastructure (Oh & Reuveny, 2010). In the agricultural sector, storage refers to increased commodity stockholding (Baldos & Hertel, 2015), regional grain emergency reserves (Bren D'Amour et al., 2016) or the establishment of a surplus of critical commodities (Lewis & Witham, 2012). Moreover, the agriculture sample includes specific agricultural/food policy, such as to support food exporting countries in their adaptation efforts by promoting the implementation of fair and ethical food policies (Brás et al., 2019).

One more category is specific to the agriculture sample. Broadly categorized as agricultural adaptation, this includes measures taken at the location where the climate change impact occurs to reduce adverse effects. These measures, however, can also be initiated by those indirectly affected through trade dependencies for example. Options include land management (Ejaz Qureshi et al., 2013; Kummu et al., 2014; Puma et al., 2015), change in farming practices (Chatzopoulos et al., 2020; Chen et al., 2008; Costinot et al., 2014), and irrigation (Fuss et al., 2015; Laube et al., 2012; Stokeld et al., 2020).

While the detailed analysis of adaptation options above only considers the peer reviewed literature, we find that the gray literature discusses and suggests an even broader spectrum of adaptation options. In particular, Hildén et al. (2020) provide further examples for trade-related regulatory interventions, such as trade agreements and export bans. Regarding the research gaps on climate change and adaptation, Wilton Park et al. (2019) emphasize the need for developing assessment methodologies for transboundary risks along trade pathways with a particular focus on climate shocks and slow-onset changes and their financial implications.

Concerning the need for knowledge sharing among different actors, several reports strengthen this argument by referring to required collaborations among institutions (Nadin & Roberts, 2018), countries (Davis et al., 2016), and communities (Bailey & Wellesley, 2017). Magnan et al. (2015) specify that monitoring can also provide information for the UNFCCC for tracking adaptation and TCRs at the global scale, and Bailey and Wellesley (2017) state its usefulness to the OECD for identifying investment priorities.

Finally, the gray literature also offers further suggestions regarding the management of supply chains with greater relevance for the industrial sectors, where supply chains are usually longer and more complex than in agricultural and food producing sectors. With a focus on the German economy and TCRs, Peter et al. (2020) conclude that a broader diversification of supply chains reduces the dependency on individual countries and resilience can be further increased by diversifying subcontracting cooperation in sourcing intermediate inputs from abroad. In the agriculture sample, Benzie and John (2015) suggest that diversification is particularly important for import-dependent countries aiming at reducing their exposure to both international and domestic price volatility.

3.3.2 | How are the different options discussed? Identification of potentials for conflict

Several papers raised the issue of potentially adverse effects that may arise for countries that have not been involved in the decision-making process toward the implementation of the respective option. Table 2 shows how adaptation options across the different categories are discussed in the literature, i.e. positively, neutrally, or whether they show potentials for conflict.

While trade policy seems an obvious option to address climate risks that are transferred along trade pathways, our analysis reveals that this adaptation option bears a large potential of conflict. This is significant for agriculture and the only negatively discussed options for other industrial sectors. These options primarily include action of one actor that leads to a decrease in food security for another actor, such as the introduction of export bans in case of low yields to ensure domestic food availability (Janssens et al., 2020; Kummur et al., 2014; Ouraich et al., 2019). Tigchelaar et al. (2018) critically discuss the crucial role of international trade in contributing to global food security in the context of a rising population, raising the need to take repercussions of policy decisions into consideration. Puma et al. (2015) emphasize the need to address the trade-offs associated with local and global resilience, which requires that countries consider balancing food self-sufficiency and import dependency.

In agriculture the common adaptation response irrigation also bears a high potential for conflict as it often involves the exploitation of a scarce resource that is also required for other purposes with food production already being responsible for 70% of freshwater use (Laube et al., 2012; Willett et al., 2019). As irrigation is highly constrained by water availability in general, extending irrigation facilities may be a poor adaptation choice in areas where water is already scarce today or a decrease in average precipitation is projected such as in South Africa (Calzadilla et al., 2014).

Negative repercussions should also be considered when using tools such as planning and coordination, risk management, and agricultural/food policy. The common critique for these adaptation measures targets the prevalent practice of addressing issues in isolation without integrating further policy areas and thus not controlling for potential trade-offs. One example is provided by Ejaz Qureshi et al. (2013) who find that poor agricultural planning and coordination of adaptation can lead to increases in the production of one crop but a reduction in the production of another one. Mosnier et al. (2014) also emphasize that the coordination of adaptation policies internationally should avoid negative spillover effects of local adaptation strategies to other regions and Yu et al. (2020) argue for the necessity to integrate international food trade into the other climate change adaptation approaches in the future.

For industrial sectors, the awareness of adverse effects of adaptation in the academic literature is rare. Only Chalinor et al. (2017) discuss the advantages and disadvantages of protectionist policies and its potential consequences for global market instabilities. However, similar to the agriculture literature, the gray literature on industry contains further discussion on potentials for conflict surrounding trade policy and other adaptation options. Adams et al. (2020) and Hildén et al. (2020) for example warn against the use of export bans to sustain domestic consumption as this poses an additional risk to other countries. With respect to climate finance, Peter et al. (2020) describe how adaptive actions, such as the reduction of imports from exposed countries, by developed countries can harm highly vulnerable countries and argue instead for a purposive strategy to support these countries with their challenges of adaptation and mitigation.

Also in the gray literature, risk management and planning options are criticized for climate change risks being assessed or treated in isolation from other global threats. The impacts of climate change will need to be factored in across all areas of government policy which have an international dimension (UK Foresight, 2011). Klein et al. (2017) add that the interaction of adaptation research and policy with other policy goals such as poverty eradication efforts, disaster risk reduction, and sectoral planning and development, should be considered with actors and issues increasingly depending on one another.

3.4 | Who are the key actors, what are their primary actions and where are they taken?

3.4.1 | Key adaptation options by actors

In both samples, the government is mentioned most frequently as an actor. In the agriculture peer-reviewed sample, all government actors contribute 68% to the total (single government: 32%; multiple governments: 8%, international community: 28%; Figure 4). The remaining 32% of actions are attributed to business (17%), research (14%), and non-state actors such as NGOs (1%). In the industry sample, single and multiple governments and the international community contribute a smaller share (46% in total), and business, research and non-state actors are comparatively more important

(20%, 23%, and 9%, respectively; Figure 5). The gray literature comes to a very similar conclusion with regard to key actors in agriculture and industry.

Figures 4 and 5 allocate adaptation actions to actors for each of the samples. Within the agriculture sample, both the government and the international community play a key role in trade policy (Bren D'Amour et al., 2016; Lewis & Witham, 2012; Mosnier et al., 2014), adaptation planning and coordination (Benzie & Persson, 2019; Challinor et al., 2010), knowledge creation, and risk management (Challinor et al., 2010; Lim-Camacho et al., 2017; Puma et al., 2015). Business is relatively more engaged in sectoral adaptation (changed agricultural practices, irrigation etc.), and supply chain management (Ejaz Qureshi et al., 2013; Lim-Camacho et al., 2017; Stokeld et al., 2020). Research institutions mostly engage in research activities, but also contribute to sectoral adaptation.

Within the industry sample, the main role of the government are knowledge creation and provision of transport infrastructure and storage capacities, as these later activities complement businesses in risk management and supply chain management (Becker et al., 2013; Koks et al., 2019; Oh & Reuveny, 2010; O'Keeffe et al., 2020). Businesses are also listed in the context of adaptation finance and risk sharing mechanisms such as insurance for business interruptions (Surminski et al., 2016) or supporting the resilience of suppliers (Lim-Camacho et al., 2017).

Compared with agriculture, research is mentioned in the industry sample more frequently as there seems to be a need for improved climate projections (Becker et al., 2013; Klein et al., 2017) and a better understanding on how these projections translate into threats and opportunities for industry (Gledhill et al., 2013b), as well as information concerning the availability, cost and effectiveness of adaptation (Liverman, 2016; Persson & Dzebo, 2019). The international community, multiple governments, and non-state actors, such as NGOs, are mentioned as actors in adaptation planning and coordination, finance and risk sharing, and knowledge creation.

3.4.2 | Main sites and scales of intervention

Figure 4 reveals that 40% of all adaptation options for agriculture according to the peer-reviewed literature target the source: intended to reduce TCRs where they originate. This includes measures such as changes in crop varieties, irrigation, and farm management. The second most frequent entry point are global governance structures (32%), in the context of adaptation planning and coordination, but also in the form of trade policy, knowledge creation, risk management, and research and development. According to the gray literature, the share of governance is even higher (58%) and viewed as the main point of intervention.

As adaptation at the source or via the governance structure might not be feasible, redirecting trade flows along the pathway by either trade diversification (as a policy response) or supply chain management (by private companies, e.g., between manufacturers and retailers) is identified as an alternative in 13% of papers on agriculture. Finally, a number of adaptation options addresses TCRs at the country of final destination (8%), such as increasing storage of agricultural/food products, risk management, research and development or knowledge creation (e.g., awareness raising at business level).

For trade in other industries, governance plays an even greater role (mentioned for 54% of all adaptation options). In governance, multilateral processes are particularly needed for creating knowledge on how to identify and manage TCRs in industry trade, as well as for coordinating adaptation planning across actors and sites. Yet, while global governance is viewed as the main point of intervention in the reviewed literature, Persson (2019) concludes that the insufficient recognition of adaptation as a global public good has so far resulted in limited legitimacy of global governance initiatives on adaptation. Another reason for the weak precision and obligation of global adaptation governance is found in “package deals” between mitigation and adaptation (Hall & Persson, 2018; Heuson et al., 2015).

Adaptation at source (23% of papers), path, and sink (9% each) are however also important for industry in the form of risk management and supply chain management. Finally, while the peer-reviewed literature shows a stronger focus on adaptation at the source (23% compared with 10%), the gray literature has a stronger emphasis on the country of final impact (19% vs. 9%).

4 | DISCUSSION

Overall, one notable result of this systematic review is the finding that adaptation to TCRs in trade is often closely related to other types of adaptation. In both agriculture and industry, many of the identified adaptation options are familiar to the adaptation community and well-understood. Many adaptation options, particularly those at the source, are similar to those being employed for reducing domestic climate risks, including shifting production to drought or

heat resistant crop varieties, adopting climate smart agricultural practices, and expanding storage capacity. Many adaptation options along the trade pathway (trade policy, trade diversification, supply chain management) and at the sink (agricultural and food policy, risk management) are commonly employed techniques to ensure food security and eradicate poverty, again suggesting that there is ample opportunity to learn from the experience of other related fields.

Almost 40% of papers in the industry sample (agriculture: 10%) do not specify the climate hazard and more than a quarter does not specify the risks posed to industry (agriculture: 3%). Still, even without complete knowledge of all risks, it can be beneficial to engage in certain adaptation actions. This can include building up slack resources and increasing redundancy in supply networks, as these will enhance adaptive capacity. Surminski et al. (2016) argue that acting sooner may avoid decisions that lock in vulnerability. In many cases, choices about suppliers and business structure are hard to reverse and adapting at a later stage can be slow. With relatively low costs and potentially high benefits, soft adaptation measures, such as knowledge creation or awareness-raising, are good candidates for an early adoption as they pose little risk of failure or negative consequences for other actors.

In both samples, the systemic nature of TCRs (e.g., simultaneous global breadbasket failures or globally synchronized production shocks) are not currently well-addressed by existing adaptation options (Gaupp et al., 2020; Puma et al., 2015; Tigchelaar et al., 2018), especially in industry. One plausible contributor to this oversight is the importance of supply chain transparency to identify systemic risks (e.g., Tenggren et al., 2020), coupled with low incentives for businesses to improve transparency which may reduce their comparative advantage (Gledhill et al., 2013a). Incentivizing supply chain transparency and leveraging the key roles played by private sector actors in supply chain risk management is a crucial step for improving adaptation to TCRs.

A key concern for adapting to TCRs is the possibility of pursuing adaptation actions which have negative impacts for others. There is broad agreement in the agriculture sample that protectionist policies like export bans can exacerbate supply disruptions and may lead to global food price spikes—as was the case in the wake of the 2006–2008 global food crisis (e.g., Baldos & Hertel, 2015; Chen et al., 2012; Tigchelaar et al., 2018). Many scholars also conclude that trade liberalization may be a highly effective adaptation option (e.g., Baldos et al., 2019; Brown et al., 2017; Fuss et al., 2015; Lybbert et al., 2014; Villoria & Chen, 2018; Xie et al., 2019). Others noted the “double-edged” nature of trade liberalization (e.g., Ouraich et al., 2019), or pointed to its limits especially with regard to the high geographical concentration of production or the danger of simultaneous production shocks and global bread-basket failures (Gaupp et al., 2020; Puma et al., 2015; Tigchelaar et al., 2018). Taken together, there is consensus that protectionist trade policies can be maladaptive, but there remains disagreement about the appropriate response; alternatives suggested are developing strategic crop reserves, contingency planning (Gaupp et al., 2020), genetic diversification, and diet diversification (Puma et al., 2015).

Compared with local and national adaptation, adapting to TCRs is a global public good, affecting all countries, and generating positive spillover effects in a complex, interconnected manner (Carter et al., 2021). As such, adapting to TCRs cannot simply be treated as the sum of adaptation efforts at the national level, but rather requires careful coordination across borders to effectively adapt on a global level (Hedlund et al., 2018). While roughly half of all measures in both samples refer to improving the global governance of adaptation, significant questions remain about how to design processes which are sufficiently expedient, effective, and support the most vulnerable countries and communities. A critical question for future research is which multilateral processes—including the UNFCCC, the WTO, or other policy venues—would be best suited to pursue this coordination and on what basis. In the absence of global or multilateral coordination, it is unclear how well unilateral action may substitute for it, either by states or private actors. Any such action would ideally be additional to—rather than replace—ongoing local and national adaptation efforts, serve to reduce TCRs rather than redistributing them to other more vulnerable players, and facilitate broader transformation toward climate-resilient trade (Constant & Davin, 2019; Wilton Park et al., 2019).

5 | CONCLUSION

This systematic review demonstrates that research has progressed from the recognition of TCRs as an important variant of climate risk to the assessment of how, who and where adaptation actions can be taken to reduce these risks. Yet, several gaps remain that need to be addressed in future research. First, this review reveals that some measures, such as protectionist trade policies, can generate trade-offs and have a high risk of maladaptation or climate risk redistribution. More comprehensive assessments are therefore required which not only explore the practicalities of implementing TCR adaptation measures in trade, but which consider their effectiveness, trade-offs with other measures, and the plausible

consequences for other actors. Second, while not at the center of our analysis, a significant amount of existing research focuses on the exposure of industrialized countries to TCRs, treating developing countries primarily as sources of risk. While this is not true in all cases, notably for work addressing food insecurity and hunger, many import-dependent developing countries are also likely to be highly exposed to TCRs via foreign trade (Hedlund et al., 2018).

Still, while it is clear that more research is needed, this systematic review also shows that a critical mass of evidence on adaptation to TCRs is beginning to emerge, particularly underscoring the importance of international coordination mechanisms. The design of these mechanisms is not a question that can be resolved through research alone, but rather will require careful political deliberation about which policy venues are most appropriate to manage TCRs, including how risk and the burden of adapting should be fairly shared. These discussions should urgently begin where possible, including in the context of the UNFCCC's Global Stocktake as it assesses progress toward the Global Goal on Adaptation, and provide countries and private sector actors alike an opportunity to contribute positively toward cooperative climate action and building global resilience.

AUTHOR CONTRIBUTIONS

Birgit Bednar-Friedl: Conceptualization (lead); data curation (supporting); formal analysis (equal); funding acquisition (lead); methodology (equal); supervision (lead); validation (lead); visualization (supporting); writing – original draft (equal); writing – review and editing (lead). **Nina Knittel:** Conceptualization (supporting); data curation (supporting); formal analysis (equal); methodology (equal); validation (equal); visualization (supporting); writing – original draft (equal); writing – review and editing (supporting). **Joachim Raich:** Data curation (lead); formal analysis (supporting); methodology (supporting); visualization (lead); writing – original draft (supporting); writing – review and editing (supporting). **Kevin M. Adams:** Conceptualization (supporting); writing – original draft (supporting); writing – review and editing (supporting).

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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