Understanding climate risk externalities through the global supply chains: a framework and review of the literature on existing approaches

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Abstract

Purpose – Businesses are increasingly vulnerable and exposed to physical climate change risks, which can cascade through local, national and international supply chains. Currently, few methodologies can capture how physical risks impact businesses via the supply chains, yet outside the business literature, methodologies such as sustainability assessments can assess cascading impacts.

Design/methodology/approach – Adopting a scoping review framework by Arksey and O'Malley (2005) and the PRISMA extension for scoping reviews (PRISMA-ScR), this paper reviews 27 articles that assess climate risk in supply chains.

Findings – The literature on supply chain risks of climate change using quantitative techniques is limited. Our review confirms that no research adopts sustainability assessment methods to assess climate risk at a business-level.

Originality/value – Alongside the need to quantify physical risks to businesses is the growing awareness that climate change impacts traverse global supply chains. We review the state of the literature on methodological approaches and identify the opportunities for researchers to use sustainability assessment methods to assess climate risk in the supply chains of an individual business.

Keywords Climate change risks, Supply chain performance, Extreme weather events, International business, Input–output analysis, Life-cycle analysis

Paper type Literature review

Introduction

Climate change poses imminent and future risks to the sustainability of international businesses (IBs) (Goldstein *et al.*, 2018; Oh and Oetzel, 2022; Pattberg, 2012; United Nations Climate Change, Global, 2019). IBs rely on local, national and international transport networks to enable their ability to move goods, services and people. All transportations are heavily dependent on infrastructure, which is vulnerable to extreme weather events, exacerbated by climate change. It is estimated that US$5tn is spent on infrastructure in a year, and when infrastructure fails due to climate events, it impacts not only the physical assets but also causes socioeconomic domino effects that disrupt IBs via their supply chains (Woetzel *et al.*, 2020).

The latest Intergovernmental Panel on Climate Change (IPCC) Working Group II Report (AR6) findings show that the magnitude of climate change impacts were underestimated in previous assessments (IPCC, 2022). There has been an exponential increase in calls from business groups, insurers, regulators and other stakeholders, including investors, for disclosure of climate change risks to individual businesses and their management (Deloitte Insights, 2020; Flammer *et al.*, 2021; Horner, 2021; Krueger *et al.*, 2020; Vincent, 2020). Apart

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from disclosing climate risks to stakeholders external to the firm, an understanding of these risks and their location is required for strategic managerial interventions to mitigate them. Stakeholders increasingly hold management accountable for their climate risk management practices and transparency in their disclosures (Thompson, 2018; WEF, 2022). However, given the geographically dispersed nature of IB suppliers and the interdependencies within their supply chains, management faces a crucial challenge in assessing and disclosing their climate change risks (Surminski *et al.*, 2018). Rising to this challenge requires the development of appropriate measurement methods and tools to assess risks and how risks are transmitted across sectors and international boundaries (Benzie and Persson, 2019; Challinor *et al.*, 2018).

Thus far, voluntary disclosure concerning material climate change risks is neither high nor detailed (Davidson and Schuwerk, 2021, 2022). This finding is concerning as the interaction of climate-related risks, sometimes occurring simultaneously and across various geographical regions, can significantly impact international businesses through their supply chains (Challinor *et al.*, 2017, 2018). In fact, regulators are considering mandatory disclosure rules (Kiernan, 2022), while some industry groups seek to shape their industry's disclosure content (Vanderford, 2022). Several regulatory bodies have closely followed the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD) (TCFD, 2017) and have increasingly voiced their concern and intent to regulate disclosure requirements; these regulators include the US Securities and Exchange Commission (2022), the Financial Reporting Council (Financial Reporting Council (FRC), 2021) in the UK and the International Sustainability Standards Board (International Sustainability Standards Board (ISSB), 2022). The Carbon Disclosure Project (CDP) runs an annual climate change disclosure survey based on the TCFD recommendations for companies to report and manage their environmental impacts, which the CDP then evaluates and scores. Despite the lack of requirements for mandatory disclosures, a handful of CDP respondent firms are at the forefront of the climate disclosure movement, scoring the highest A* rating from the CDP. These firms voluntarily disclose their impact on the climate, the climate's impact on them and their governance and management of climate change to CDP, which it then scores. Based on the disclosures made to the CDP in 2021, it is estimated that firms expect around US$120 bn in costs to mitigate or resolve the physical environmental risks, regulatory risks, and market risks they face in their supply chains (CDP, 2021). This suggests that firms with high quality disclosure are assessing and trying to manage their exposure to climate risk in the supply chains.

IBs are particularly susceptible to supply chain disruptions (Meixell and Gargeya, 2005; Rao and Goldsby, 2009) and uncertainty (Sharma *et al.*, 2020), exacerbated by global and diversified operations (Reeb *et al.*, 1998). Supply chain risk is generally characterized as the probability and exposure of an event that causes disruption, either directly or indirectly, in the supply chain networks (Garvey *et al.*, 2015; Ghadge *et al.*, 2012; Yatim *et al.*, 2017). For example, NIKE, when reporting to the CDP, discussed how it was exposed to chronic physical risks in its supply chain as the majority of its production facilities are in Southeast Asia, which is exposed to rising mean temperatures. This could negatively impact manufacturing and logistics productivity and continuity based on NIKE's disclosure to the CDP in 2021 (accessible on the CDP website upon registration: https://www.cdp.net/en/search). Similarly, Levis disclosed the potential financial impact it might face due to the increased severity of extreme weather events (EWE) disrupting their supply chains. They expected the potential risks to be delays in manufacturing or importation of products and increased costs to find alternative ports or warehouse facilities to ensure that the disruptions do not impact customers based on Levi Strauss and Co's disclosures to the CDP in 2020 (accessible on the CDP website upon registration as above for NIKE). Despite firms identifying climate risk in their supply chains as a material threat to their business, the frameworks each firm uses to identify and manage these risks are still unclear, making a firm-level comparison difficult.

Concerning supply chain risks, IB literature concentrates on supply chain design, risk identification and management over physical risks. Miller (1992) presents a detailed framework for ways IBs can manage risks, where natural hazards are mentioned in a list of general environmental uncertainties. Only more recently are IB scholars looking towards developing strategies for dealing with risks arising from hazards or physical climate risks (Oh and Oetzel, 2022). There are a few reasons why research on physical climate risk demands more attention. Physical risks are more immediate and tangible as they directly impact firm operations, which causes a cascading impact across supply chains, damaging infrastructure and resulting in financial losses (Woetzel *et al.*, 2020). Physical risks, especially those from EWE, are immensely difficult to plan for or predict, which makes them more damaging. In comparison, transition risk can be better planned for as it is often linked to governments' regulatory changes and policy enactment, which happens over a longer period of time. While transition risks pose significant reputational and financial concerns to IBs, it can be managed over a longer term and in line with the move to a low carbon economy. Hence, the potential of significant immediate financial implications from transition risk is comparatively lower.

Considerable academic literature examines managing supply chain risks arising from climate change (Chen *et al.*, 2015; Jin *et al.*, 2014). However, studies assessing supply chain climate risks are less common (Er Kara *et al.*, 2021; Ghadge *et al.*, 2020). While many organisations have developed climate risk assessment methods and services for businesses, these methods are proprietary and unavailable to the public (Fiedler *et al.*, 2021; UNEP Finance Initiative, 2021). Grey literature on climate risk assessment models produced by not-for-profit and research organisations, such as the World Risk Index (WRI) (Welle and Birkmann, 2015) and the Global Climate Risk Index (CRI) (Eckstein *et al.*, 2021) can inform the scope of existing models.

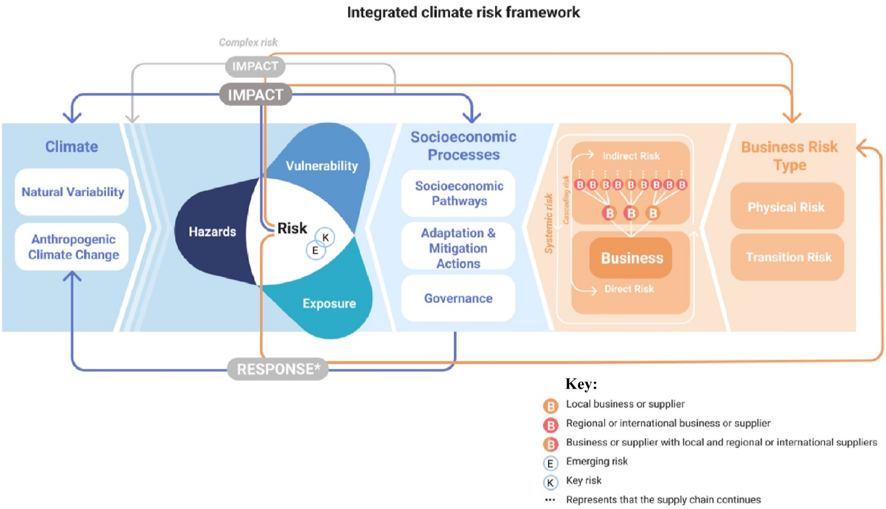
Various methodologies are commonly used to assess supply chain impacts (Ness *et al.*, 2007; Sala *et al.*, 2015). These methods are referred to as sustainability assessment methods. Sustainability assessment methods respond to the increasing need to assess non-economic indicators, such as environmental and social impacts associated with activities, for example, consumption and production. They also enable the enumeration of supply chain disruptions, which include climate-related hazards (Koks *et al.*, 2019). However, it is unclear whether these methodologies have been considered in the IB literature assessing climate risks and what opportunities exist for their use in climate risk assessments.

This paper reviews scholarly literature examining how physical climate risk has been assessed in supply chains to inform improved mitigation strategies. We start by defining climate risk and describing the methods capable of assessing supply chain impacts. We then present our review methodology, which is based on a scoping review framework by Arksey and O'Malley (2005) and the PRISMA extension for scoping reviews (PRISMA-ScR) (Tricco *et al.*, 2018) framework. We discuss the results of the 27 empirical and conceptual studies selected for our review. We conclude by presenting a synthesis and our interpretations of the literature reviewed and suggesting a way forward for future research.

Terminology

Climate risk

According to the IPCC, climate risk refers to "*the potential for adverse consequences for human or ecological systems*" (Reisinger *et al.*, 2020, p. 4), arising from the dynamic interactions between climate-related hazards and the exposure and vulnerability of human or ecological systems to those hazards. Alone, climate change is not a risk; it is the interaction of climate change or the hazard with *the evolving vulnerability and exposure of systems that culminate* in risk (see the blue part of Figure 1) (Oppenheimer *et al.*, 2014, p. 1050). *Hazards* or climate-related impacts, describe the climatic driver of a risk (Reisinger *et al.*, 2020). Hazards can be acute, such as EWE, like floods or cyclones or chronic, such as rising sea levels and increased temperatures (Guo *et al.*, 2021). *Exposure* is defined broadly as the presence of people, places, ecosystems, economic, social and cultural assets and vulnerability is defined as the predisposition to be adversely affected (Oppenheimer *et al.*, 2014). *Vulnerability* and exposure are predominately the results of human interactions and socioeconomic processes. The interaction between climate risk and the broader economy, society and environment can



Note(s): The IPCC diagram (left in blue) contains several slight modifications to the original IPCC risk framework: 1) the IPCC risk framework does not contain 'RESPONSE*', which was added by the author, given that the IPCC also recognized the need for responses to be considered as a factor that can impact risk (Reisinger *et al.,* 2020). We inherently include greenhouse gas emissions and land-use change as a climate-related response, for example, if organizations reduce/increase greenhouse gas emissions in response to risk. 2) An additional 'IMPACT' was added to represent *complex risks* that magnify the overall risk based on the hazard. In the business risk framework (right in orange), it is important to note that each business along the supply chain would experience risks as direct risks and have their supply chains where they would experience indirect risks. This demonstrates the complexity of assessing risk in supply chains

Source(s): Figure by authors, adapted from Figure 19-1 Chapter 19 in: Oppenheimer, M., M. Campos, R.Warren, J. Birkmann, G. Luber, B. O'Neill, and K. Takahashi, 2014: Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099

Figure 1.
An integrated climate risk framework

culminate in varying degrees or types of risk. The IPCC identifies climate change as a complex risk symptomatic of multiple climate hazards coinciding with subsequent risks. Several additional risk types are pertinent to the scope of this paper and are used throughout to describe the nature of climate-related risks. They are systemic and cascading risks. *Systemic risks* arise from an initial localized failure but can trigger widespread disruptions to a system (King *et al.*, 2015; Simpson *et al.*, 2021). *Cascading risks* occur when an event or trend initiates other risks, where interactions can be one-way or create feedback loops (Simpson *et al.*, 2021).

In the business literature, climate risk refers to risks organisations face. The term climate risk gained popularity after the establishment of the TCFD in 2015 (TCFD, 2017). Commonly, climate risk is divided into two categories: physical and transition risks. Physical risks, similar to the IPCC understanding of climate hazards, can be acute or chronic, such EWE and longer-term climatic shifts or sea-level rise, respectively (In *et al.*, 2022; Simpson *et al.*, 2021; Surminski *et al.*, 2018; Tsalis and Nikolaou, 2017). Chronic and acute risks can impact the operations of a business directly and indirectly through its supply chain (Clapp and Sillmann, 2019; TCFD, 2017). For example, an acute risk, such as a cyclone can disrupt operations for the business in the country in which the business operates or if the cyclone occurs elsewhere, can impact the business's operations via the supply chains. Transition risks refer to the risks arising from the transition to a low carbon economy and can include regulatory, litigation, technology or reputational risks (Arnell, 2016; Pattberg, 2012). For example, the Carbon Border Adjustment Mechanism (CBAM), a carbon levy on products from countries lacking serious pollution reduction programmes in the European Union, which is expected to come into force in 2023, will result in millions of dollars in tariffs on high-polluting exporters (Besser, 2021).

The two framings of climate risk, by the IPCC and the TCFD, have yet to be integrated. We adapt the IPCC framework on climate risk to incorporate transition and physical risks experienced by businesses (Magnan *et al.*, 2021), represented diagrammatically above (Figure 1). This figure combines the IPCC risk framework (left in blue) (Oppenheimer *et al.*, 2014) with the depiction of the sources of business risk (right in orange) in a comprehensive framework for examining climate-related risk propagating in businesses supply chains. In the IPCC risk framework (see Oppenheimer *et al.*, 2014, pp. 1046), "climate" (e.g. factors influencing climate) and "socioeconomic processes" (e.g. societal conditions and development pathways) drive the factors that constitute risks (Oppenheimer *et al.*, 2014). We include businesses as a driver of socioeconomic processes, which are increasingly informed or driven by business innovations. The IPCC and the United Nations Framework Convention on Climate Change (UNFCCC) recognise the need for businesses to drive climate action and climate safe and resilient development (IPCC, 2022).

Sustainability assessment methods

Since the World Commission on the Environment and Development (WCED) published the report "Our Common Future" in 1987, sustainable development and sustainability have become mainstream terms (Brundtland, 1987). Broadly, sustainability considers economic, social and environmental dimensions across intra- and inter-generational scales. Today, the United Nations Sustainable Development Goals (SDGs) encapsulate global cooperation to achieving and improving sustainability and sustainable development. Reporting and measuring sustainability is instrumental in cataloguing progress towards the SDGs or sustainability more broadly (Ness *et al.*, 2007). In the business management literature, it is widely recognised that you "cannot manage what you cannot measure". The sustainability assessment methods are used to measure progress towards sustainability and are reliable tools used across governments and businesses. Sustainability assessment methods often inform decision-making on managing or reducing embodied environmental and social impacts of products and services across their entire value chains (Duchin and Levine, 2014, p. 1968). Much research catalogues and categorises the methods available to assess sustainability Ness *et al.* (2007) produce a framework based on three main categories: indicators/indices, product-related assessments and integrated assessment tools. Sala *et al.* (2015) produce a comprehensive sustainability assessment approach, defining the common methodologies selected in different assessments. Across these studies, two common sustainability assessment methods applied in the context of climate change are input–output analysis and life-cycle analysis (LCA). While other sustainability assessment methods exist (see Ness *et al.* (2007)), the existing research and applications of both IO and LCA are particularly relevant to questions on climate risk, which we outline below.

Input–output (IO) analysis uses the data from economic input–output tables that capture the flow of monetary goods and services in an economy to model various supply chain impacts across the sectors and regions (Leontief, 1936). IO-based methods, including multiregion input–output analysis (MRIO) and environmentally extended input–output analysis (EEIO), have been applied in sustainability-related studies seeking to examine the carbon footprints of households (Druckman and Jackson, 2009), businesses (Demeter *et al.*, 2022), sectors (Heihsel *et al.*, 2019; Malik *et al.*, 2018; Zhang and Wang, 2016) and countries (Hertwich and Peters, 2009). They are also used to assess the supply chain impacts of disasters (Huang *et al.*, 2021; Lenzen *et al.*, 2019) and cross-border impacts embodied in trade (Wang *et al.*, 2019; Wiedmann and Lenzen, 2018). LCA traces and quantifies resource or emissions use per unit of product over the life cycle of a product (Odeh and Cockerill, 2008; van der Velden *et al.*, 2015). Hybrid IO-LCA methods have been developed to overcome the limitations of IO and LCA taken separately (Yu and Wiedmann, 2018). In our paper, sustainability assessment methods represent IO or LCA methods.

These sustainability assessment methods are relevant to questions concerning climate risks arising in supply chains for IBs. Concerning transition risks, which may include increasing liability over greenhouse gas (GHG) emissions; it is possible to enumerate the GHG emissions arising in supply chains using sustainability assessment methods. For example, LCA and IO analysis are quantitative methodologies capable of linking the data from the economy or a company with physical information on GHGs to produce such assessments (Malik *et al.*, 2018). Concerning physical risks, however, fewer sustainability assessment methods enable the quantification of economic and non-economic impacts arising from supply chain disruptions, including hazards exacerbated by climate change. IO analysis is often used in this context, albeit to the authors' knowledge, it has never been extended to consider how the supply chain impacts of a hazard impact a particular business. Based on the constraints of IO analysis to model sectoral and economic resolutions, it would need to be integrated with LCA analysis to ascertain the impact on a business (Wiedmann *et al.*, 2009). As this paper focuses on physical risk, the most relevant of these applications is the ability of sustainability assessment methods to assess the cascading impacts of climate-related events.

Methods

We used a systematic scoping review to identify peer-reviewed journals to understand how climate risk is assessed in supply chains (Arksey and O'Malley, 2005). Systematic scoping reviews are more rigorous than scoping reviews alone, and commonly, IB literature reviews adapt systematic review frameworks to canvas the literature and propose future research directions (Kano *et al.*, 2020; Papanastassiou *et al.*, 2020). We adopt the five-step framework developed by Arksey and O'Malley (2005) (Figure 2), and adhere to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines – extension for scoping reviews (Tricco *et al.*, 2018) to outline the study screening process and report the results.

Key research questions

This review explores whether the sustainability assessment methods (as defined above) have been used to assess physical climate risks in global supply chains of IBs. As illustrated in the section above, sustainability assessment models are often used to assess sectoral and regional supply chain impacts and do not (yet) do so for a specific business. We therefore, hypothesise that a novel opportunity exists to extend the sustainability assessment methods to incorporate this capability. Further, to the author's knowledge, no paper systematically reviews the scientific and interdisciplinary academic literature on the use of sustainability assessment methods in global supply chains as they relate to assessing climate risk for businesses. This literature review aims to confirm the hypothesis by canvassing this research gap in the existing literature. We focus on physical climate risks as it is sporadic, imminent and tangible, compared to the risk from transition to a low carbon economy, which is longer term, enduring and potentially managed over several decades.

Answering this research question is important as, for IBs, risk assessment and management are incomplete without supply chain considerations. Globalisation has enabled many positive benefits for IBs, such as outsourcing talent and reducing costs. As Oh and Oetzel (2022) highlight, research on hazards and their implications for IBs cannot be ignored. This makes it even more necessary for research to focus on sustainability assessment methods within the global supply chains to help quantify physical climate risks so that IBs can have appropriate risk management strategies for unprecedented climate-related events. A growing body of literature canvasses the effects climate change will have on global supply chains (Ghadge *et al.*, 2020; Pankratz and Schiller, 2019). However, none look at novel ways to quantify physical risk using the sustainability assessment methods.

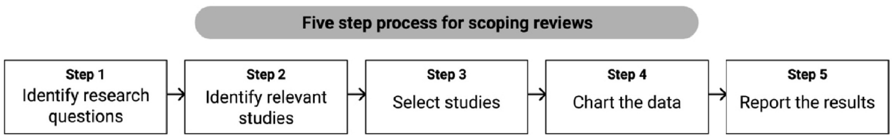
To do so, firstly, this review seeks to understand:

1. What is the scope of academic literature assessing climate risk assessments in supply chains?

While we hypothesise that sustainability assessment methods will be used across the literature answering this question, we are not confined by only examining research with the same methods. Rather, we want to understand how they are used in the broader literature considering supply chains in climate risk assessments. This means that methods outside the two sustainability assessment methods described above and the sustainability literature, other methods may appear. However, in answering this question, this paper reveals how sustainability assessment methods have been used to assess physical climate risks in global supply chains. The second question is the crux of the review and intends to confirm our hypothesis: that an opportunity exists to extend the sustainability assessment methods to individual businesses. In doing so, we seek to explore the following:

2. Are sustainability assessment methods used at the level of a business? If not, how sustainability assessment methods can be applied to an individual IB to quantify its exposure to physical climate risks in its supply chain?

Through the first part of this question, we unveil the trends in studies using sustainability assessment methods and highlight the gap in the extant literature. The second part of the



Source(s): Figure by authors

Figure 2.
The five step process followed in this study based on Arksey and O'Malley's (2005) scoping review framework

question is covered in the discussion, where we elaborate on the potential of sustainability assessment methods in this context.

Search strategy

We limited our search criteria to a meaningful search string aligned with our research questions to identify the literature to include in this scoping review. These terms were searched across titles, keywords and abstracts to constrain the research results on climate risk/assessments (Search 1). Our second search string (Search 2) expanded to include synonyms of "climate change", "supply chain", "risk" and "assessment". We do not include the term "physical" because climate risk encompasses physical risks. Notably, we also included the Boolean operator AND with synonyms for "business" to capture business-specific literature (Table 1). Finally, we did not include the date as a parameter, searching for all studies up to and including March 2022.

While sustainability assessment methods are some of the dominant methods in interdisciplinary or sustainability-related literature to assess supply chain impacts, other modelling techniques exist in discipline-specific literature. Therefore, we did not choose to isolate our search to only studies that adopted sustainability assessment methods mentioned in the terminology section. Instead, we wanted to understand the existing methods used to assess climate risk in supply chains and assess the role and potential of sustainability assessment methods for future research.

Electronic databases consulted include Scopus, ScienceDirect, ABI/Inform and Web of Science. Scopus and ScienceDirect are well-established databases that capture most of the peer-reviewed scientific and interdisciplinary academic literature. Unlike other reviews in the IB literature, we do not confine ourselves to IB and business-specific journals (Caprar *et al.*, 2022), as the observed literature on climate risk comes from disparate disciplines requiring a multidisciplinary approach. ABI/Inform was chosen because it is a business-specific literature database (Bauer *et al.*, 2018; Kunz *et al.*, 2020). Web of Science was selected as it includes Wiley and Emerald publications, which contain important supply chain management journals (Fan and Stevenson, 2018). Additionally, we supplemented our search strategy, adopting a multilayered strategy, including hand-searching, snowballing and cross-referencing to identify other relevant literature (Adams *et al.*, 2016). We consulted

Database	
	Search 1 – parameters (indicates wildcard operator used in the search so that additional terms were captured. For example, "climat*" captures "climate" and "climatic")*
Scopus ABI/Inform** Web of Science	("climat* change") AND ("supply chain*") AND ("risk assess*")
ScienceDirect***	("climate change" OR "climatic change") AND ("supply chain" OR "supply chains") and ("risk assessment")
	Search 2 – parameters
Scopus ABI/Inform Web of Science	("climat*" OR "climat* change" OR "anthropogenic* climat* change" OR "global warming") AND ("supply chain*" OR "indirect impact*" OR "value chain") AND ("assess*" OR "analysis") AND ("risk*") AND ("business*" OR "organisation*" OR "firm*" OR "company")
ScienceDirect	("climate change" OR "global warming") AND ("supply chain" OR "indirect impact") AND ("assessment" OR "analysis") AND ("business" OR "firm") AND ("risk")

Note(s): *Indicates wildcard operator used in the search. **ABI/Inform did not enable a search across keywords, so only titles and abstracts were scanned. ***For ScienceDirect, we were limited by eight Boolean operators, so we selected the broadest terms possible for inclusion. Additionally, ScienceDirect does not support wildcards

Table 1.
Literature search parameters

the Social Science Research Network (SSRN) and the first ten pages of Google Scholar using our Search 1 parameters, owing to the limited functionality of both engines to narrow the search parameters to the abstract and keywords.

Study selection

Our study selection process was guided by stringent inclusion and exclusion criteria (Arksey and O'Malley, 2005). The criteria in our scoping study required that the study be about climate risk assessments in supply chains (Table 2). We applied these criteria in the abstract screening. However, if the relevance of a study was unclear from the abstract, we read the paper in its entirety before determining its inclusion. Review articles, books, chapters, forums and conference hearings were also excluded, as it is common in more systematic literature reviews (Adams *et al.*, 2016; Ghadge *et al.*, 2012; Ghadge *et al.*, 2020; Munn *et al.*, 2018). Figure 3 shows the flow diagram for screening the dataset by adapting a PRISMA approach.

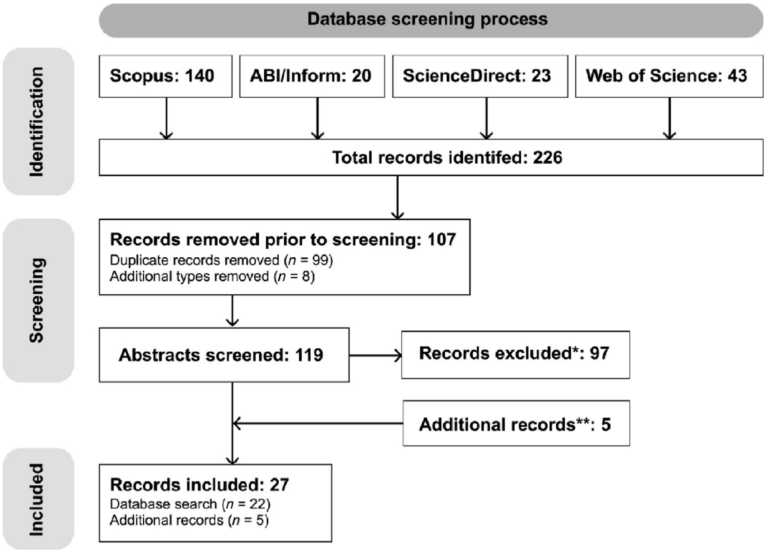
Data charting and analysis tool

We developed a consolidated database of the 27 papers reviewed, identifying key aspects important to our research scope using Excel (Table 3). Our database included: a) the author, b) the year, c) the journal in which it was published, d) the method type (e.g. quantitative), e) the specific method, f) the proxy for climate risk, g) the topic and whether it involved a sector or business and h) the region used as a case study as recommended by (Arksey and O'Malley, 2005).

In addition to analysing the data in our database, we use Bibliometrix, a quantitative bibliography mapping tool, to present an initial descriptive analysis of the results. This approach enables a more nuanced analysis of how the literature is situated in the context to one another and the relevance of the citations. We downloaded two separate data files with our articles from the World of Science and Scopus databases, following Caputo and Kargina (2021), to merge the two datasets together. These data are then run through Bibliometrix, which Linnenluecke *et al.* (2019) recommend for literature reviews in the business and management fields.

Code	Definition	Justification
NOTCRA	The topic was either not on a *supply chain* climate risk assessment (Doubleday *et al.*, 2013) or examined climate risk but did not *assess* it explicitly (Weinhofer and Busch, 2013)	Ensures that methods to present climate risk assessments are the focus of the research
NOTCR	The topic was not on climate risk explicitly. For example, the paper referred to climate risk in the abstract, but it was not the focus of the research	Ensures that the topic of the paper is related to climate risk broadly. For example, a paper examining drought risk extremes from climate change was included
OTH	The topic was about sustainable supply chains, quantifying carbon footprints or other topics not related to climate risk (Palea and Santhià, 2022)	Ensures that we examine the literature on climate risk specifically
RVA	The topic was related to climate change adaptation or mitigation, vulnerability or resilience and unrelated to a risk assessment of the latter	Ensures that the literature included is narrowed to assess risk, not mitigation/adaptation. Research that developed climate risk assessments to reduce vulnerability was included

Table 2.
Exclusion criteria and justification



Note(s): *represents sources excluded based on exclusion criteria. **describes sources found outside database searches

Source(s): Figure by authors

Figure 3. Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines – extension for scoping review (Tricco *et al.*, 2018) flowchart designed by the authors

Results

Descriptive statistics

A total of 226 records were initially identified from the databases during the search period in January–March 2022. After removing duplicates and following the screening of the remaining 119 records, 22 studies remained for inclusion in our review (Figure 4). Five additional studies were included based on snowballing search techniques. Of the studies reviewed, 88% were published since 2015 (Figure 5), which coincides with the establishment of the TCFD (TCFD, 2017). These results suggested the limited scope or research on climate risk in supply chains, which is pertinent to our first research question.

The Bibliometrix results present valuable information on the core themes across the articles and the most highly cited papers. Figure 6 shows that climate change risk and supply chain performance are the dominant themes in the reviewed literature. This also validates that our inclusion criteria helped us locate literature related to our research question. Further, the papers analysed in the coming sections are closely related to physical climate risks, as represented by the dominance of EWE in the word cloud (Figure 6). Figure 7 reveals that of the 27 papers included in our review, the top five most cited were published since 2015. The one outlier was a paper in 2010. This finding aligns with the year the Paris Agreement was ratified, and the first conversations on climate risk for businesses were discussed.

The methods

Quantitative methods. Quantitative methods such as IO analysis, hybrid LCA models, computational and mean-variance methods and machine learning models, were used in 54% of papers reviewed (N = 15). Sustainability assessment methods were the most applied category of quantitative methods (N = 5). This was unsurprising as these are well-established methods to quantify impacts propagating in the supply chains (Dietzenbacher

Table 3. Database of included literature

Author/s	(Year)	Journal	Method type*	Method/s	Proxy for climate risk	Sector (S) or business (B): detail	Region/s
Vinke *et al*	(2022)	*Climate Risk Management*	Quant	Modelling	Disaster (drought)	(S): Transport (ports)	Germany
Lin and Ma	(2022)	*Environmental science and policy*	Quant	Machine learning (ML) (change point analysis and spike point analysis)	Weather (extreme weather events)	(S): Food	France
Nakano	(2021)	*Journal of cleaner production*	Quant	Multiregion input–output (MRIO) analysis	Disasters (various)	(S): Automotive	USA, China, Japan and Germany
Er Kara *et al*	(2021)	*International Journal of Production Research*	Mixed methods	Cognitive mapping, surveys and systems dynamic (SD) modelling	Natural resources (raw materials) and logistics (operations)	(S): Performance	Not defined
Simpson *et al.***	(2021)	*One Earth*	Qual	Analysis and content analysis	Temperature (heatwaves)	(S): General	Europe
Ali and Ismail	(2021)	*Supply Chain Management*	Mixed methods	Interviews and questionnaires	Temperature and disasters (bushfire, heatwaves, floods and droughts)	(S): Food	Australia
Bonnafous and Lall	(2021)	*Natural hazards and earth system sciences*	Quant	Computation	Weather (extreme precipitation) & disaster (drought)	(S): Raw materials (bauxite, iron-ore, copper and gold)	Global
Wang *et al*	(2021)	*Resources, Conservation and Recycling*	Quant	Bayesian network model	Weather (increased precipitation)	(NA): Other (Water–energy–food nexus)	China
Ghadge *et al*	(2020)	*Technological Forecasting and Social Change*	Quant	SD modelling approach	Temperature (general)	(S): Energy (bioethanol (corn and switchgrass)	North America
Stokeld *et al*	(2020)	*Climatic change*	Quant	Combination of three models for climate, crop yield and trader climate risk exposure	Temperature and disasters (general)	(S): Food	Brazil

(*continued*)

Table 3.

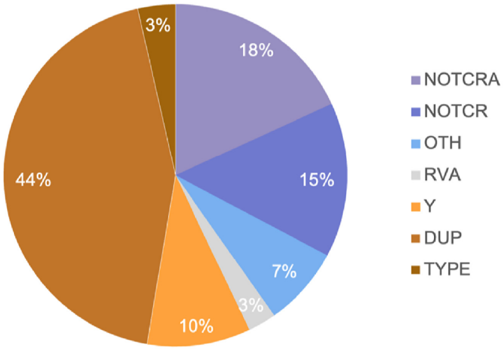
Author/s	(Year)	Journal	Method type*	Method/s	Proxy for climate risk	Sector (S) or business (B): detail	Region/s
Tenggren *et al*	(2020)	*Journal of Environmental Planning and Management*	Qual	Interviews	Weather (extreme weather events)	(B): General (export oriented businesses)	Sweden
Schaefer *et al*	(2019)	*Journal of cleaner production*	Quant	Monte Carlo Analytic Hierarchy Process (MCAHP)	Natural resources (water risk)	(B): Specific (Proctor and Gamble unit))	Global
Zhao *et al*	(2019)	*Journal of cleaner production*	Quant	MRIO	Natural resources (water scarcity)	(S): Water	Global
Srinivasan *et al*	(2019)	*Computers and industrial engineering*	Quant	Mean-variance models	Temperature	(S): Agriculture (food sourcing decisions)	South America, central Africa, Oceania, United States of America, Western and Eastern Europe and Australia
Yang *et al*	(2018)	*Transportation Research Part D: Transport and Environment*	Mixed methods	Fuzzy-Bayesian risk analysis and interviews	Environmental driver (sea-level rise and storm surges)	(S): Transport (ports)	China
Groundstroem and Juhola	(2018)	*Environment systems and decisions*	Qual	Comparative analysis	Various	(S): Energy	Finland, Sweden, Norway, Denmark and Iceland
Lim-Camacho *et al*	(2017)	*Global Environmental Change*	Mixed methods	Comparative analysis	Disaster (droughts, floods and fires)	(S): Natural resources (mining), Aquaculture (fisheries) and Food (rice)	Australia
Nakano	(2017)	*Mitigation and adaptation strategies for global change*	Quant	Life-cycle assessment framework for adaptive planning (LCA-AP)	Disease (dengue)	(S): Labour	USA, China, Japan, Germany, India and Brazil
Meinel and Abegg	(2017)	*Global Environmental Change*	Mixed methods	Surveys and interviews	General	(B): Manufacturing	Austria
Tsalis and Nikolaou**	(2017)	*Business strategy and the environment*	Mixed methods	SD approach	Regulatory risks	(B): General (performance)	Not specified

(*continued*)

Table 3.

Author/s	(Year)	Journal	Method type*	Method/s	Proxy for climate risk	Sector (S) or business (B): detail	Region/s
Monasterolo *et al*	(2017)	*Climatic change*	Quant	Development of novel indices	Transition risk (greenhouse gas emissions)	(B): General exposure	Austria, Belgium, Cyprus, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Malta, the Netherlands, Portugal, Slovakia, Slovenia and Spain
Otto *et al.***	(2017)	*Journal of Economic Dynamics and Control*	Quant	MRIO analysis	Weather (extreme weather events)	(S): Manufacturing	Japan
Kim and Lee	(2016)	*Sustainability*	Mixed methods	ISO management approach and surveys with consultants	Weather (extreme heat and cold) and disaster (extreme precipitation and snow)	(B): Bank	Korea
Aviso *et al*	(2015)	*Biomass and Bioenergy*	Quant	Fuzzy inoperability input–output model (IIM) work and supply-reduction framework	Disaster (typhoons)	(S): Energy (biodiesel)	The Philippines
Hseih	(2014)	*Natural Hazards*	Mixed methods	Disaster risk analysis	Disaster (tsunami and debris overflow)	(S): Transport (port)	Taiwan
Bierkandt *et al*	(2014)	*Environment Systems and Decisions*	Quant	MRIO analysis	Weather (extreme weather events)	(S): Machinery	Japan
Jacxsens *et al*	(2010)	*Food Research International*	Qual	Conceptual modelling	Disease (microbiological food safety)	(S) Food (general)	Not applicable

Note(s): *Quant = Quantitative, Qual = Qualitative
The rows shaded grey represents the papers that apply the sustainability assessment methods to assess climate risk

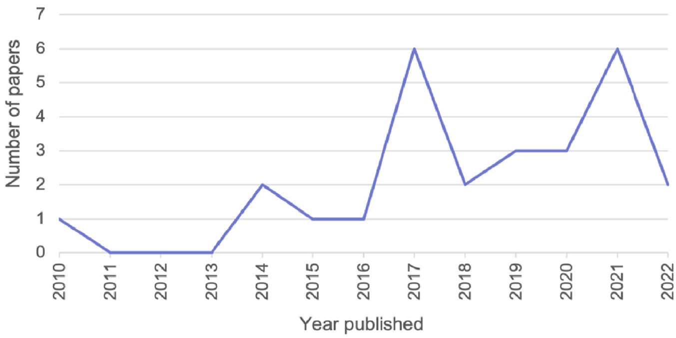


Note(s):

NOTCRA	not on a climate risk assessment
NOTCR	not on climate risk
OTH	unrelated (i.e., examined the sustainability of supply chains)
RVA	was specific to resilience, vulnerability or adaptation but did not present a risk assessment
DUP	duplicate papers
TYPE	research types excluded for analysis
Y	represents studies that were included

Source(s): Figure by authors

Figure 4. Screened results based on literature database search



Source(s): Figure by authors

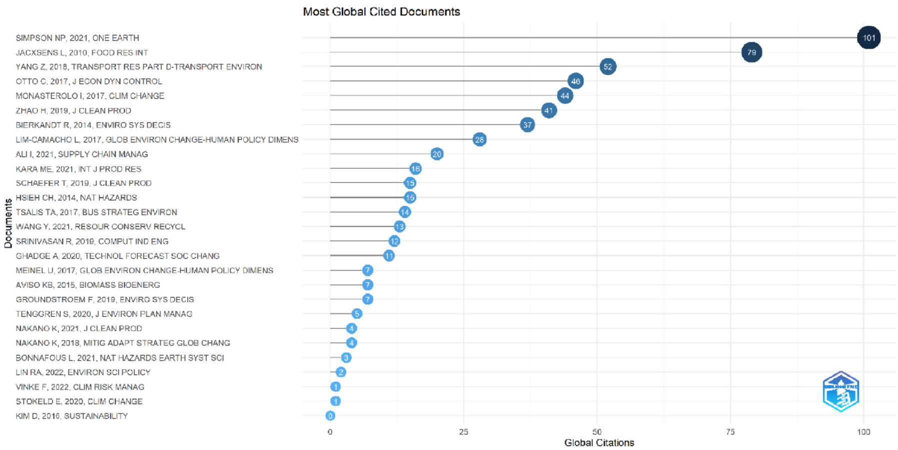
Figure 5. Number of papers included in the review by publication date (n = 27)

et al., 2020; Schulte in den Bäumen *et al.*, 2015; Wiedmann, 2009). It is worth noting that all studies using sustainability assessment techniques (N = 6) examine risk at an industry-sector level (i.e. an aggregation of businesses into one homogenous sector) and not at an individual-business level. The other quantitative methods demonstrate the diversity of potential methods to assess climate risk. However, the diversity of these quantitative methods renders comparing and assessing the consistency of the methods to be impossible.

Aviso *et al.* (2015) assessed the economic risks of climate change associated with the 5% mandatory biodiesel blending in the Philippines using a fuzzy inoperable input–output (IIM) model. Their model shows that climate risk manifests in the highest economic losses in coconut farming, manufacturing and other agriculture. A critical connection made is that increased dependency on biofuel increases the risk to agriculture caused by climate change.

Source(s): Figure by authors

Figure 6. Word cloud of core themes created using Bibliometrix



Source(s): Figure by authors

Figure 7. Most cited literature included in the review created using Bibliometrix

Nakano (2017) used MRIO analysis to examine the cascading effects on labour losses from an increased risk of contracting dengue fever. A later paper by Nakano (2021) also used MRIO analysis to quantify climate risk on economic and labour factors using the automotive industry from the United States of America, Germany, Japan, China and the UK, as a case study. A notable aspect of this study is that risk is assessed based on a climate-related disaster risk factor (CDRF), used as an indicator encompassing both vulnerability and hazard. Bierkandt *et al.* (2014) and the later study by the same co-author Otto *et al.* (2017), developed a model called Acclimate to examine how disasters propagate in supply chains. The Acclimate model incorporates MRIO databases to enumerate the supply chain impacts. However, the studies are both focused on disaster impacts; they are situated in the context of being able to inform a risk assessment, so they were included for review. Zhao *et al.* (2019) applied MRIO analysis to examine virtual water scarcity risk (WSR) from climate change embodied in global supply chains. This was analysed concerning two scenarios: the business as usual (BAU) scenario, which is aligned to Representative Concentration Pathway (RCP) 8.5

and an optimistic scenario, which is aligned to RCP 4.5. An observation is that this extrapolation identifies the importance of climate risk at a business-level, yet does not seek to quantify it. For example, businesses within mining and agriculture sectors depend on freshwater resources and thus, would be heavily implicated because of water scarcity. Regardless, they highlight how WSR arising from climate change is connected via supply chains (Zhao *et al.*, 2019).

The remaining quantitative studies (60%) employed vastly different methods. Monasterolo *et al.* (2017) used computational methods to develop novel indices to analyse two main dimensions of investors' vulnerability to climate risk, exposure of investors to climate risk and market share of financial actors weighted by its contribution to GHG emissions. Bonnafous and Lall (2021) also used computational methods; however, their model showed how the clustering of climate extremes affects natural mineral supply chains. Their study contributes to the underdeveloped field of hydroclimatic risk clustering and its impact on risk exposure, which is relevant for global portfolio managers in natural minerals. Stokeld *et al.* (2020) developed several modelling components to present Brazil's soy crop traders' exposure to climate risk. A benefit to their methodology is that they demonstrate insight into the subnational variation of climate risks on a particular crop, which may be vital for future adaptation and planning. Srinivasan *et al.* (2019) applied mean-variance models to assess climate risk in food sourcing decisions, though their analysis solely uses climatic data in sourcing decisions, ignoring other socioeconomic considerations. Lin and Ma (2022) adopted machine learning algorithms to identify the risk of EWE and price fluctuations for 25 food supply chains. A novel contribution of the method they employed is that they can show how highly temporal-correlated supply chains, such as sugar, bread and cereals, resulted in price jumps that were quick to reflect extreme temperature spikes, with the opposite being valid for lowly temporal-correlated supply chains. Wang *et al.* (2021) used Bayesian Network (BN) modelling to create a multivariable scenario simulation, with only one input representing climate risk – extreme precipitation. A limitation is that they do not specify supply chain risks in the BN model but instead focus on the impact on supply-demand risk arising from the input changes. Vinke *et al.* (2022) used a 1D flow solver, given its application in flood forecasting coupled with a Python package for logistics simulation, to calculate the cascading effects on inland shipping in the Rhine, Germany.

Qualitative methods. Qualitative methods, including interviews and surveys, were used in 11% of the papers reviewed (N = 4). Simpson *et al.* (2021) synthesise literature describing complex climate change risks to establish a holistic framework for risk assessment that encompasses the risks less developed by the IPCC reports. In their research, Tenggren *et al.* (2020) conducted qualitative interviews with large manufacturing businesses that produce their goods in Sweden but have high export shares to understand how they understand climate risks in business supply chains. Sweden is the case study selected because of its many import-dependent and export-oriented industries; thus, climate risk to businesses is likely to manifest through global supply chains. This study supports findings in previous studies (Linnenluecke *et al.*, 2015), showing that businesses mostly regard climate change as a strategic risk and not as an operational one. This literature provides important insights into how climate risk is perceived and qualitatively assessed.

Researchers have designed qualitative frameworks for assessing risk and understanding how climate risk propagates in supply chains. Groundstroem and Juhola (2018) developed a conceptual framework to identify potential cross-border impacts on energy systems in the Nordic countries. Their methodology involved comparing statistical data from all Nordic counties to conduct a comparative analysis to demonstrate the supply chain risks. A contribution of their assessment is that it was one of the earlier academic papers to explore the cross-border impacts of climate change, specifically on the energy sector across various regions. Jacxsens *et al.* (2010) also created a conceptual framework but assessed various risks of fresh produce microbiological food safety. Hsieh (2014) developed a risk map based on a literature review and results from workshops and interviews with experts to assess where the risk arises in the port of Taipei.

Mixed methods. Mixed methods represented 35% of the studies reviewed (N = 8). The most used method was systems dynamic (SD) modelling (Er Kara *et al*., 2021; Ghadge *et al*., 2020; Tsalis and Nikolaou, 2017); a computer-based simulation approach representing how systems respond to external influences. SD modelling also demands a qualitative approach to developing the causal loop diagram. Er Kara *et al.* (2021) identified the linkages between climate-related natural weather events and supply chain performance. To overcome biases in constructing their causal diagram, they surveyed 62 supply chain managers before transforming it into a stock and flow diagram. Their SD model, supported by climate scenarios, demonstrates how supply chain performance decreases under worsening climate scenarios when evaluated through effectiveness and efficiency. Tsalis and Nikolaou (2017) used STELLA modelling software to create their SD model, called the climate change risk assessment (CCRA) model, to analyse the effects of regulatory risks on corporate performance. Their methods were divided into a qualitative component, the creation of the causal loop diagram, and a quantitative component, using STELLA modelling to reveal the supply chain climate risks on corporate performance. Ghadge *et al.* (2020) applied an SD approach to assessing the extent of potential disruptions arising from climate change. Their input data were based on various sources in the literature as well as expert consultation. Using eight scenarios, four for each crop (corn and switchgrass), they demonstrated the effects of the extreme RCP pathways on yield and non-yield periods. Their model showed that climate risk manifests through decreased yield, production and shortages for final consumers. The results indicated that bioethanol availability may decrease by one-fourth by 2060. The SD modelling studies conceptually present a holistic assessment of climate risk in supply chains. However, since the construction of the SD model is based on a causal loop diagram, which the authors of the paper usually do, there may be increased biases.

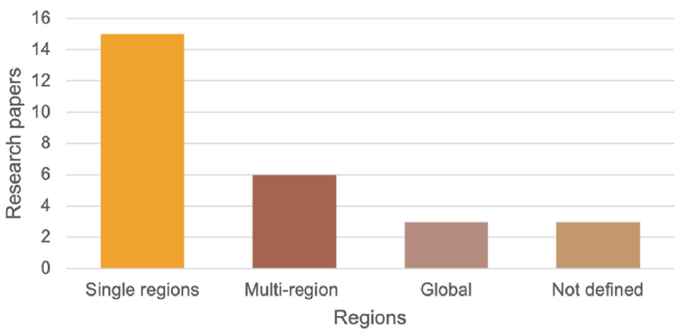
Four studies combined social research methods such as surveys and interviews into their methodologies. Ali and Ismail (2021) used qualitative interviews and quantitative questionnaires to determine whether social capital impacts climate risks between small and medium-sized enterprises (SMEs) in the Australian citrus industry and their "*portfolio of inter-organizational relationships or associations*" (Ali and Ismail, 2021, p. 5). Their independent variables are climate risk, consortia and social capital, with their dependent variable being performance. To test their hypothesis, they used regression analysis. Their results showed that SMEs associated with consortia and those nurturing social capital face reduced climate change risks. This finding suggests that cooperating on climate risks with similar SMEs can reduce climate risk and could be tested in the industry to demonstrate its success. Meinel and Abegg (2017) also used a combination of interviews and quantitative surveys to assess how manufacturing firms perceive climate risk. Their results are analysed based on a sectoral comparison, which they use to generate hypotheses on potential drivers of entrepreneurship. Yang *et al.* (2018) combined data from surveys from experts across China with a fuzzy Bayesian risk analysis to show how port adaptation measures influence their climate change risk. They also use their model to assess the cost-effectiveness of the adaptation measure. Schaefer *et al.* (2019) constructed a water risk index for firms by using Monte Carlo Analytic Hierarchy Process (MCAHP) to derive weights for each metric obtained from survey data.

Lim-Camacho *et al.* (2017) used a comparative analysis to examine how complex and simple supply chains react to climate-related risks. Complex supply chains are those with many interacting suppliers, and in contrast, simple supply chains may have few suppliers for any producer. They used a simulation approach adapted from Plaganyi *et al.* (2014) coupled with a qualitative literature review to map the supply chain nodes. Kim and Lee (2016) developed a web-based application assessing climate risk based on the International Standard Organisation (ISO) 31000 approaches. The ISO 31000 is an internationally accepted risk management guideline that provides principles, frameworks, and processes for managing risk for organisations (ISO, 2021). It represents the only model, in this review, to look at direct climate risks to businesses while also touching on supply chain risks. The main limitation of the model is that it could not show how the climate risk propagates through supply chains beyond Korea.

The perspective

Food-related risk assessments were the most researched area (26%). This trend is consistent with developments in the supply chain literature focusing on food supply chains (Ghadge *et al.*, 2020). Lin and Ma (2022) specifically examined the impact of EWE in France on 25 food supply chains during the 15 years from 2005 to 2019. Stokeld *et al.* (2020) also focused on food supply chains, but only the soy supply chain. Unlike Lin and Ma (2022) and Stokeld *et al.* (2020), Srinivasan *et al.* (2019) identified the interconnectedness of supply chains and the risks they are exposed to by evaluating food sourcing decisions for banana, coconut and barley. Ali and Ismail (2021) adopt a similar approach, examining how climate risks can be reduced by establishing consortia between the Australian citrus industry SMEs. Following the food sectors, energy or energy production was a common topic or sector assessed (Aviso *et al.*, 2015; Groundstroem and Juhola, 2018). All other papers solely focused on climate risks from a sectoral or event perspective, and a few studies focus on various risk types at the firm-level. Tsalis and Nikolaou (2017) considered the impacts and risks caused by climate change between different and critical variables of a business's operation and climate change. They investigate this through an SD approach and use qualitative data from five Greek SMEs to confirm their causal loop diagram. Schaefer *et al.* (2019) developed their water risk index by applying it to a case study using available supplier data from Proctor and Gamble.

The concentration of case studies was in single countries (Figure 8) (Ali and Ismail, 2021; Bierkandt *et al.*, 2014; Ghadge *et al.*, 2020; Groundstroem and Juhola, 2018; Lin and Ma, 2022; Otto *et al.*, 2017; Simpson *et al.*, 2021; Tenggren *et al.*, 2020). Several studies incorporated the supply chain risks facing developing countries in their models (Nakano, 2017, 2021; Srinivasan *et al.*, 2019). Two studies focused solely on developing countries. Aviso *et al.* (2015) focused on the ripple economic effects of climate risk in the Philippines, while Stokeld *et al.* (2020) examined how trader risk exposure increases under climate scenarios across interconnected soy supply chains in Brazil. Zhao *et al.* (2019), Schaefer *et al.* (2019) and



Source(s): Figure by authors

Figure 8. Concentration of regions represented in the literature review

Bonnafous and Lall (2021) are the only studies to assess climate risk across global supply chains, identifying which sectors are most impacted by virtual water scarcity and examining how global land area facing extreme precipitation or drought risk affects mining commodities, respectively. Limited research assessing cascading global climate risk may be due to complex supply chain interactions that are challenging to model using international databases and limited data. Additionally, conducting climate risk assessments may be challenging, given that definitions of climate risk vary. However, global assessments are crucial as businesses often operate globally.

Proxy for climate risk

Around 12 studies (44%) examined climate change through increased frequency of weather events and climate-related disasters. Lin and Ma (2022) used EWE, sourced from European Climate Assessment and Dataset, as a proxy for climate risk, while extreme precipitation indices were used by Bonnafous and Lall (2021), Wang *et al.* (2021) and Kim and Lee (2016). Nakano (2021) developed an index of disasters based on those exacerbated by climate change. In one study by Aviso *et al.* (2015), increased typhoon risk was represented as climate risk and selected as a risk to biofuel production based on other literature (Stromberg *et al.*, 2011). Vinke *et al.* (2022) use flooding as a proxy for climate risk based on a rigorous literature review. Bierkandt *et al.* (2014) and Otto *et al.* (2017) simulated shocks to the Japanese manufacturing sector using various data from past climate-related EWE that resulted in a loss of production output. Four studies (15%) used temperature increase as a proxy to represent how climate change manifests as a risk (Ghadge *et al.*, 2020; Simpson *et al.*, 2021; Srinivasan *et al.*, 2019; Stokeld *et al.*, 2020). For example, Srinivasan *et al.* (2019) used GHG emissions and temperature increases inherent in RCP 6.0 developed by the IPCC to represent climate risk to examine crop suitability and risk calculation in food sourcing decisions. Ali and Ismail (2021) adopted a qualitative approach in defining their climate risk proxies. They reported that SMEs in the citrus industry found temperature increases, bushfires, droughts and flooding represent climate risks to their operations. Natural resource depletion and scarcity are also used as proxies. Zhao *et al.* (2019) presented the existing literature demonstrating how water scarcity arises from climate change. Schaefer *et al.* (2019) also assesses that water risk is an inherent climate-related risk, however, in reports from the CDP, only 28% see water as a risk to their business.

Instead of developing a proxy for climate risk, Er Kara *et al.* (2021) modelled two scenarios arising from climate change on logistics operation and raw material availability. Only Nakano (2017) cited the World Health Organisation, which developed quantitative risk assessments, factoring in how climate change increases dengue fever cases (WHO, 2014). This risk is modelled across the labour force across specific regions (Nakano, 2017). The use of disease as a proxy for climate change is highly relevant given the links between human health and climate change (Paz, 2021; Watts *et al.*, 2018). Several studies examined the effects of climate risk on both sectors and businesses (Monasterolo *et al.*, 2017; Tsalis and Nikolaou, 2017); however, climate risk was represented as a regulatory risk and not a physical one.

Limitations

Our search and exclusion criteria were deliberately designed to be specific, given our research interest in examining how climate risk is *assessed* in supply chains. For example, findings showing that extreme weather influenced by climate change are associated with lower and more volatile earnings and cash flows (Huang *et al.*, 2018) do not reveal how climate change risk is assessed. Furthermore, the design of our keywords may also have resulted in similar research being excluded. We attempted to overcome this by including several synonyms in our second search. More comprehensive systematic reviews apply fewer keywords per string to ensure coverage of all literature. As we were interested in conducting a scoping review, this was irrelevant. Secondly, grey literature was excluded as the focus was on academic research presenting climate risk assessments. However, it has been observed that climate risk assessments may be more common in the grey literature (Ghadge *et al.*, 2020). To overcome this limitation, we consulted grey literature in our discussion.

Discussion and pathways forward

Through our systematic scoping review, we found that 27 papers or ~20% of the literature we screened for quantifying risk in supply chains (total papers = 119), presented a methodology to do so. Within the review of the 27 papers, several key trends emerge. Firstly, the literature on climate risk assessments and supply chain risk are extensive yet separate, and this observation corroborated the findings in Ghadge *et al.* (2020a, b). Within the business literature, according to Ghadge *et al.* (2020a, b), climate change has received the least attention in supply chain risk–management literature owing to the challenges of predicting climate-related disruptions. However, there is continued interest in understanding supply chain risks and cascading impacts outside the business literature, demonstrating ongoing challenges in defining optimal approaches for quantifying physical climate risks. Secondly, as part of our review, we sought to understand how supply chain climate risks were assessed, which draws attention to the models used. As detailed in the methods section, many methods were employed across the literature (Table 3). While it is out of the scope of this review to assess the potential for all methods to assess physical climate risk to IBs, interested readers can explore other related literature reviews by (Ghadge *et al.*, 2020). We present a critical assessment of the methods employed below.

Sustainability assessment methods were the most used in the studies reviewed (20%). This was expected, given that they are well-established models for tracing supply chain impacts (Dietzenbacher *et al.*, 2020). The climate-related risks assessed included floods and other EWEs (Aviso *et al.*, 2015; Nakano, 2021), disease (Nakano, 2017) and natural resource scarcity (Zhao *et al.*, 2019). These studies represent how MRIO can be used across various types of climate risk to demonstrate how it impacts the economy through output and productivity loss. Interestingly, the physical climate risks facing businesses via their supply chains was only examined in four studies, through the lens of performance (Ali and Ismail, 2021; Er Kara *et al.*, 2021) or transition risks (Monasterolo *et al.*, 2017; Tsalis and Nikolaou, 2017). Each of these studies employed various methods, yet none employed sustainability assessment methods to assess risk for a specific business. In contrast, research that assessed risk to businesses, such as Katopodis *et al.* (2021), who used the Climate Risk Assessment Matrix (CRAM) to assess climate risk to facing a Greek oil refinery, does not include supply chain risks.

As observed in our review, besides literature adopting sustainability assessment methods to assess climate risk, quantitative and mixed-methods approaches (comprising systems dynamic modelling and qualitative techniques such as interviews and surveys to develop causal loop diagrams) offer alternative options for assessing climate risk. As mentioned, SD models were the next common quantitative method employed. The SD model employed by Ghadge *et al.* (2020) (based on the systems theory) uses simulation-based approaches to understand the behaviour between variables and their interaction over time. A benefit of their approach is that their proposed model is estimated using a commercial simulation software and can forecast results for 40 years (from 2020 to 2060). The ability to forecast results has important implications for businesses wanting to understand future risks. However, assumptions in terms of the boundaries of the model and included variables are inherent limitations of this approach (Er Kara *et al.*, 2021).

A benefit of qualitative approaches is that greater insight into the specifics of the business can be ascertained, especially through interviews and surveys (Bewley, 2002). For example, in Er Kara *et al.* (2021), 62 surveys with business representatives from various industries determined the most prominent risks based on the practitioner's point of view. However, sometimes biases are inherent in sampling processes; in the same study, the survey was shared with over 240 industry contacts (Er Kara *et al.*, 2021). In their survey of 102 firms in the Austrian Alps of Tyrol, Meinel and Abegg (2017) discuss the limitations of such a specific case study focus. They highlight that due to limited replies from each sector, no statistical tests could verify the results from comparative analysis. Therefore, while greater specificity can be gained, qualitative approaches can introduce biases. Causal loop diagramming can reveal important patterns in the supply chain activities of businesses, yet rely on the interpretation of the activities based on interviews or other literature (Ghadge *et al.*, 2020). This means that the final causal loop diagram can introduce additional biases. Also, where it is used to develop the SD model, causal loop diagramming does not consider the regional distribution of supply chains (Ghadge *et al.*, 2020).

Sustainability assessment methods offer greater spatial resolution than these approaches, which is important for international businesses regarding borderless climate risks. These methods could address concerns raised in several studies regarding the difficulty in accessing data on the impact of climate change on SC operations (Er Kara *et al.*, 2021), which could be achieved using sustainability assessment methods. Furthermore, it offers the ability to quantitatively identify sectoral risk hotspots. By identifying sectoral hotspots, businesses and policymakers can understand the vulnerabilities in existing supply chains. The identification of risk hotspots could spur greater research into this area and inspire greater industry collaboration regarding climate change adaptation in supply chains. However, there are some inherent challenges in adopting sustainability assessments at a business-level, the most notable being the need to collect disaggregated expense data from the business, which might be unavailable due to confidentiality issues and disaggregated damage data of climate-related hazards (see (Koks and Thissen, 2016) for detail on what data are needed to use sustainability assessment methods for disaster analysis).

These trends reveal the scope of academic literature developing and applying sustainability assessment methods in supply chain climate risk assessments, which was the first research question presented in this study. While an assessment of the strengths and weaknesses between sustainability assessment methods and other methodologies in this review is outside the scope of this paper, we can ascertain that sustainability assessment methods are well-suited to questions concerning physical climate risks. Our second research question sought to understand the role and potential of sustainability assessments informing assessment of business risks. As we found in this review, sustainability assessment methods have not been applied in the context of individual businesses. Rather, they are used to assess risks at a sectoral and regional-level. The reason for sectoral and regional resolutions is that MRIO analysis is based on national input–output tables, which collate data from statistical agencies on the monetary transactions between sectors and regions. Integrating business data into input–output tables would require a hybrid modelling approach, as in Malik *et al.* (2015). In their research, they coupled an Australian MRIO model with engineering process data on algal bio-crude production to undertake a hybrid life-cycle assessment for measuring the direct and indirect impacts of producing bio-crude. However, as demonstrated in their research, a notable challenge is obtaining disaggregated (detailed) expenditure data from companies.

Future research pathways

Addressing underestimations of risk. In disclosing climate risk, businesses routinely underestimate the magnitude of physical and supply chain risks (Goldstein *et al.*, 2018;

Sakhel, 2017). Goldstein *et al.* (2018) analysed CDP climate disclosures of the top 500 companies by market capitalisation and found that the firms identify and disclose transition risk as material to their business at about twice the rate of physical risks. This is surprising given just in 2022, natural disasters resulted in direct economic losses estimated at US$313 bn, out of which only US$132 bn was insured (Aon, 2023), indicating the impact climate events can have on the economy and the underestimation of climate risk by firms. Yet, managing risk is a key objective of IBs (Miller, 1992). The ability of sustainability assessment methods to capture indirect risks is highly relevant for businesses interested in assessing total climate risk (Fiedler *et al.*, 2021). Consider a business evaluating the likelihood of an immediate risk, such as a storm, impacting their business headquarters. The likelihood of a storm of a certain magnitude may be assessed as increasing from a once-a-year event to a twice-a-year event under future climate scenarios. However, this assessment ignores that the business may depend on inputs from another business that operates in a location, where the likelihood of another climate-related hazard significantly would impact their production capacity. Zscheischler *et al.* (2018) recommend accounting for regional risk differences to develop more robust climate risk assessments. While researchers such as Romilly (2007) present risk indices for locations in which businesses operate, their research does not consider in-time interactions across supply chains. Novel ways to apply MRIO analysis could overcome risk underestimation challenges by revealing how climate risk manifests in a business's supply chain, thus enabling businesses to work collaboratively with their suppliers on adaptation and mitigation strategies. In 2022, a report by the CDP stated that most of the supply chain disclosures did not include assessments on broader supplier impacts, such as Scope 3 emissions (CDP, 2022). Additionally, considering tipping points in a risk assessment would help businesses contextualize the ripple effects of the risk they may face under future climate change (Magnan *et al.*, 2021; Simpson *et al.*, 2021). Finally, future risk assessments should consider that climatic hazards can interact with non-climatic hazards simultaneously, exacerbating overall risk nonlinearly (Oppenheimer *et al.*, 2014).

Integrating climate models and supply chain risk assessments for businesses. Climate models facilitate managerial understanding of future climate-related risks and opportunities under various scenarios (TCFD, 2017). Notably, some sustainability assessment methods, such as MRIO analysis and LCA, can be utilized with climate change scenarios relevant to businesses, such as those presented by the IPCC. Zhao *et al.* (2019) demonstrates this opportunity by incorporating the change in water scarcity risk under climate change scenarios. One challenge in conducting climate risk assessments that rely on climate model data is that communicating risk across time horizons may vary considerably from a business versus scientific perspective (Fiedler *et al.*, 2021; Weber *et al.*, 2018). The World Risk Report by the World Economic Forum surveyed experts and business leaders and indicated that risks in 0–2 years are short term, 2–5 years are medium term and 5–10 years are long term (WEF, 2022). In comparison, the scientific community and the IPCC have a broader time horizon for climate impacts defined in 20 year increments, where the short term is between 2021–2040, the midterm is between 2041–2060 and the long term is between 2081–2100 (IPCC, 2022). This disparity indicates that adopting sustainability assessment methods into climate risk assessments requires careful consideration of representing risk time horizons.

Developing open-source risk models for transparency. Climate risk assessments can promote societal and policy responses, and can promote public knowledge of climate risks, impacts and consequences (IPCC, 2022). However, risk assessment models, particularly those used by businesses and climate services, are not open source (Fiedler *et al.*, 2021). For example, during the 2020 CDP reporting period, companies projected costs up to US$120 bn across their supply chains arising from environmental and climate risks in the next five years (CDP, 2021). However, how businesses reporting to the CDP estimated their supply chain climate risks was not disclosed. A report by the United Nations Environment Programme

Finance Initiative presents an overview of commercially available methodologies or climate services that assess the physical risks of climate change. Unsurprisingly, only four companies of the 19 surveyed provide the methods for public use but do not provide the source code (UNEP Finance Initiative, 2021). Researchers have called for more transparent models and processes to overcome potential biases in a business's private climate assessment models or self-reporting (Walenta, 2020). Therefore, future research designing open-source climate risk assessment models for businesses (and businesses uptake of these models) is a valuable opportunity.

Conclusion

Given the genuine and legitimate pressures on firms to manage and report climate risk to external stakeholders, more work is required at the individual business level. Research shows that the more complex the supply network, the greater the risk (Harland *et al.*, 2003). Businesses must understand more comprehensively how climate risk cascades through their increasingly complex and dispersed supply chain networks to develop effective resilience and mitigation strategies (Er Kara *et al.*, 2021; Ivanov and Dolgui, 2019). Beyond the direct risks of climate change, businesses also face ongoing regulatory risks propagating through supply chains as large economies move to net zero. Interconnected supply chains have offered companies worldwide opportunities to expand operations into geographically distant regions and lower production costs; however, this expansion comes with considerable risk as climate impacts in one region could cause severe disruptions to global supply chains, and regulatory changes can ripple through the system. This review indicates a gap in the literature for using sustainability assessment methods, such as MRIO analysis, LCA, and hybrid MRIO-LCA methods to assess physical climate risk across a businesses supply chains. The results presented and the opportunities identified come at an opportune time, given the findings underpinning the IPCC Working Group II Report (AR6) (IPCC, 2022).

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