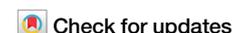


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# Facing the storm: Developing corporate adaptation and resilience action plans amid climate uncertainty

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Climate hazards disrupt global value chains and business operations, leading to €52 billion in losses for the European Union in 2022 alone. In response to this escalating crisis, there is a need for corporate climate adaptation and resilience strategies (henceforth: CCAR) to effectively integrate climate risk challenges into strategic planning. Despite this urgency, there is a shortfall of research synthesising the drivers, strategies, and outcomes of corporate adaptation and resilience. Our study addresses this gap by conducting a systematic literature review to elucidate the academic status quo. From an initial dataset of over 3000 publications, we narrowed the sample to 66 papers, which specifically focus on these topics in the private sector. Grounded in this comprehensive review and regulatory observations, we delineate a CCAR typology to define the key elements required for a corporate approach to physical climate risks. This typology is translated into an actionable business adaptation framework, offering a clear path to begin the adaptation journey. Our in-depth content analysis contributes to the existing literature by identifying two main themes and several gaps: Current research covers the drivers, detailing why companies embark on such initiatives. Another stream focuses on how companies adapt, examining strategies to overcome these climate risks. However, work on the effectiveness and outcomes thereof is scarce. Consequently, our study delineates six trajectories for future research, the outcomes of which can serve as catalysts for advancing future CCAR efforts.

The climate crisis and its physical risks have become a pressing issue for humanity—every tenth of a degree beyond the 1.5 °C target has the potential to dramatically alter the world as we know and understand it today through cascading physical climate risks<sup>1</sup>. Increasing in frequency and intensity<sup>1</sup>, these range from acute risks (e.g., floods, heat waves, wildfires) to chronic impacts (e.g., changing precipitation patterns, rising average temperatures)<sup>2</sup>. One of the very (financially) costly consequences is that human-made systems, such as global value chains, are substantially disrupted<sup>3</sup>. Beyond these physical impacts, the private sector faces liability<sup>4</sup> and transition risks<sup>5,6</sup>, for instance being sued for lack of climate initiatives or misleading reporting thereupon<sup>4,7</sup>. Thus, climate risks become relevant not only to the natural environment but also to our human systems, i.e., our economies, that are dependent on it<sup>1</sup>.

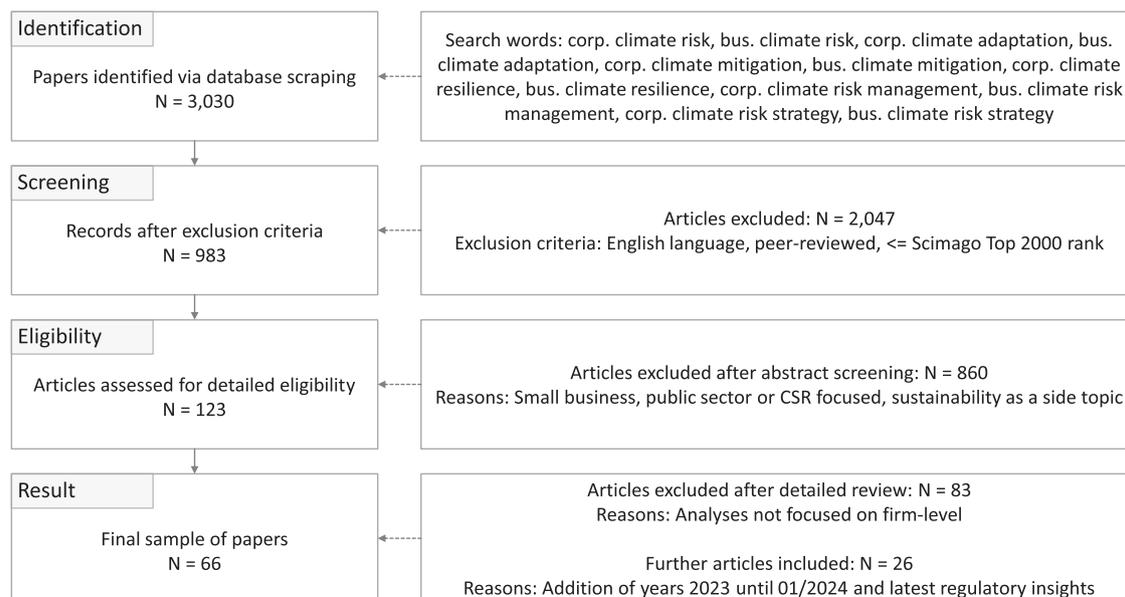
In today's business reality, there are numerous examples of physical consequences building up to a systemic risk that threatens financial stability<sup>6,8,9</sup>. For instance, in 2021, Hurricane Ida caused losses of \$65 billion

in North America<sup>10</sup>. Only one year later, US companies were exposed to extreme droughts that built up to supply chain costs of \$20 billion<sup>11</sup>—simultaneously, floods caused economic losses and reconstruction costs of over \$31 billion to Pakistan's economy<sup>12</sup>. These disruptions demonstrate the challenges that the private sector faces globally. Various weather extremes can strike in a relatively short timeframe, causing infrastructural damages, supply chain disconnections, wreaked production sites<sup>3,13</sup>, or surges in global raw material prices<sup>14</sup>—to name but a few. Following these incidents, it is common for businesses to shut down operations, at least temporarily, to accommodate repairs and rebuilds, if financially viable<sup>15,16</sup>.

Decarbonisation aims to tackle the root cause of climate change, but insufficient progress<sup>17</sup> leads to intensifying rather than declining feedback loops, requiring corporates to prepare for these challenges<sup>18</sup>. This is where corporate climate adaptation and resilience (henceforth: CCAR) comes in—it acknowledges the reality of a changing climate and focuses on adjusting to a world where some consequences are now inevitable and where

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**Fig. 1 | Literature search strategy.** The flow diagram, generated according to PRISMA, describes the process of the systematic literature review, including all steps from the identification of the initial sample to the analysis of the final sample. Each

step details the number of articles that were included or excluded and the reasons for their inclusion or exclusion. The abbreviations have the following meaning: corp. corporate; bus. business.

requirements for corporate disclosure of physical risks are growing<sup>4</sup>. Despite this scientific clarity and emerging regulations, most corporates currently do not understand how to prepare for the acute extremes that we are already seeing today, nor how to adapt to the long-term chronic impacts<sup>19</sup>. This calls for a translation of scientific evidence and risk disclosure standards into the operationalisation of corporate adaptation<sup>20</sup>. To date, no such conversion has been conducted and there is limited research on the corporate level. This is noteworthy given the vital role businesses play in adaptive efforts<sup>21</sup> to maintain societal functioning amid surging climate crises. Consequently, it is crucial to identify what motivates globally operating businesses to engage in adaptation, how they do it, and the results of these efforts.

Although corporate climate adaptation and resilience have recently been addressed by some prominent publications<sup>14,22–25</sup> and regulations<sup>26,27</sup>, we still see three gaps. Firstly, even though existing research has broadly investigated overall climate risk impact, small businesses’ issues with infrastructure, agriculture, tourism, or the public sector’s role, a synthesis of CCAR knowledge that corporates can leverage has been largely overlooked. Secondly, the absence of a concise, universally applicable typology that defines the key elements of CCAR at the firm-level leaves too much room for interpretation or missteps and thus presents another gap. Lastly, from a practical lens, there is a lack of operationalisation of academic knowledge coupled with reporting insights into an actionable first-step adaptation guide. This could assist the private sector in informing its strategies, operations, and disclosure approaches. From a theoretical perspective, this would also serve as a basis for identifying areas requiring further research. In an effort to close these gaps and thereby answer manifold research calls<sup>14,25</sup>, we conduct a systematic literature review aiming to bring clarity to the following questions:

- (i) What is and what is not known about CCAR from an academic perspective?
- (ii) What defines CCAR for practice?
- (iii) What adaptive steps can businesses take to enhance their climate resilience?

As our study’s foundation, the systematic literature review presents the latest adaptation and resilience insights, specifically focused on the private sector (i). Thoroughly evaluating existing academic knowledge at the firm-level, we contribute to the current literature by identifying what is known

about corporate adaptation drivers, strategies, and outcomes. By incorporating observations on recent regulatory developments in climate risk disclosure, we enrich these academic findings and establish the foundation for our subsequent analyses to answer research questions (ii) and (iii). This synthesis enables us to delineate a CCAR typology at the firm-level, which defines the key elements required for a corporate approach to physical climate risk challenges. To the best of our knowledge, we are among the first to turn these theoretical contributions into practical firm-level guidance. More specifically, we translate the CCAR elements of the typology into an actionable business adaptation framework, thereby offering corporates a clear path to begin their adaptation journey. This is designed to bridge the gap between the current state of business and the identification, adaptation and eventual disclosure of climate risks. Lastly, we highlight central research blindspots. Going forward, topics like the measurement of CCAR outcomes or conducive regulatory incentives warrant further investigation (Box 1 elaborates on research pathways).

## Building an academic foundation for CCAR Methods

To compile the dataset of relevant articles, we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) procedure<sup>28</sup> and began by (1) searching four central databases at the hand of 12 keywords (please refer to Fig. 1 or the Supplementary Methods 1 for further information on the selection of keywords.): EBSCO, Web of Science, Scopus, Science Direct. Between 2010 and 2022, a total of 3030 papers were published. As a second step, we (2) filtered via exclusion criteria (English language, peer-reviewed, Scimago Top 2000 rank), which left us with 983 articles. Lower-ranked journals were included to account for the fact that CCAR is a new topic of academic interest. Subsequently, we (3) systematically analysed all 983 articles’ abstracts to distill those that do indeed address sustainability in the private sector. Due to a multitude of unsuitable works (e.g., unrelated, small business, public sector or CSR focused, sustainability only as a side topic), we eliminated 860 papers.

This narrowed the dataset down to 123 articles for a detailed review of corporate adaptation. Lastly (4), we dropped 83 further papers that did not focus on firm-level analyses. This distilled a sample of 40 papers, which are all corporate-focused and specifically encompass adaptation drivers, levers, and outcomes. In light of recent regulatory changes regarding climate risks,

we conducted a further search for important accounting and regulatory research articles that were not identified in our initial search. Specifically, we focused on articles relevant to the period between 01/2023 and 01/2024 using forward snowballing and cross-referencing techniques to review the dataset. Once we added these articles, our final sample increased to 66 papers (please refer to Supplementary Table 1, which contains the full list). An in-depth analysis of all articles was performed by applying a review framework we developed to cover the breadth of potential CCAR topics (please refer to Supplementary Discussion 1 for limitations and Supplementary Methods 2 and 3 for details on the review framework). The review framework's functionality was also tested with other business sustainability academics. Systematically extracting data from the final sample, we found manifold insights.

### Research foci

For instance, the sample demonstrates geographical and topical patterns. As such, the CCAR literature originates from the Global North, offering a perspective mainly from the private sectors of highly developed nations. This trend is no surprise, considering that these regions wield sizeable global corporate influence and resources to devote to adaptation and resilience research<sup>29,30</sup>. This raises questions about the equitability of these efforts. It prompts consideration of the disparity between corporations with the financial means to pre-emptively adapt and well-functioning institutions surrounding them that provide regulatory support or guidance, versus those in developing countries that already face some of the most acute climate risks<sup>1</sup>. This also suggests that a key adaptation aspect of corporates' global operations might be ignored, i.e., their suppliers and manufacturers at the start of the value chain.

Beyond geographical implications, our analysis displays a limited sectoral focus, as only half (45%) of the articles are industry-specific (percentages represent the relative emphasis of an adaptation aspect). Among these, over three quarters (36% overall) originate from two broader sectoral spectrums: (1) manufacturing and producing industries (18%), (2) management and finance (18%). All others contribute about two to three percent each. This is substantiated when examining business functions, as roughly a fourth of the papers display a concentration on organisations' accounting & finance (27%). It is mirrored by production/operations (21%) and followed by other streams dedicated to management, administration, marketing and sales (15%) and sustainability (6%). Notably, about a third of the papers do not entail information regarding business functions (30%). Given these foci, we delineate a research tendency towards manufacturing, resource-intensive businesses and the management thereof, which points to the need for strategic planning in response to the high operational impact of these physical risks.

### Review insights

Investigating adaptation to physical climate risks in the selected papers, two clear streams were detected: (1) Current CCAR literature provides considerable knowledge on antecedents, with the majority of the papers analysing the driving forces that lead corporates to engage in adaptation. (2) Another substantial body of work examines adaptation strategies, meaning what levers do corporates employ to overcome physical climate risks.

(1) A key conclusion from our analysis is that particularly a company's value chain positioning, as well as its resulting climate risk exposure and managerial awareness thereof, are key predictors of its engagement in adaptation. Specifically, over two-thirds (71%) of the underlying literature elaborates on adaptation-inducing factors. As a corporate's exposure to climate risks<sup>31,32</sup> has a measurable negative impact on revenue potential or performance indicators like sales<sup>33–35</sup> or stock market performance<sup>36–38</sup>, it plays a critical role in whether and how businesses adapt. The papers emphasise that action upon these risks can only be taken if there is managerial awareness thereof. Thus, internalities like key personnel's (climate) risk perception<sup>22,39–43</sup> and general integration of risk management into corporate processes<sup>24,31,44</sup> are adaptation facilitators. Beyond these firm-internal factors, externalities are also acknowledged as crucial determinants,

such as institutional pressures<sup>45–47</sup> like specific climate regulation<sup>48,49</sup>, disclosure requirements<sup>50,51</sup> or a company's embeddedness and inter-dependencies within its business network<sup>52,53</sup>.

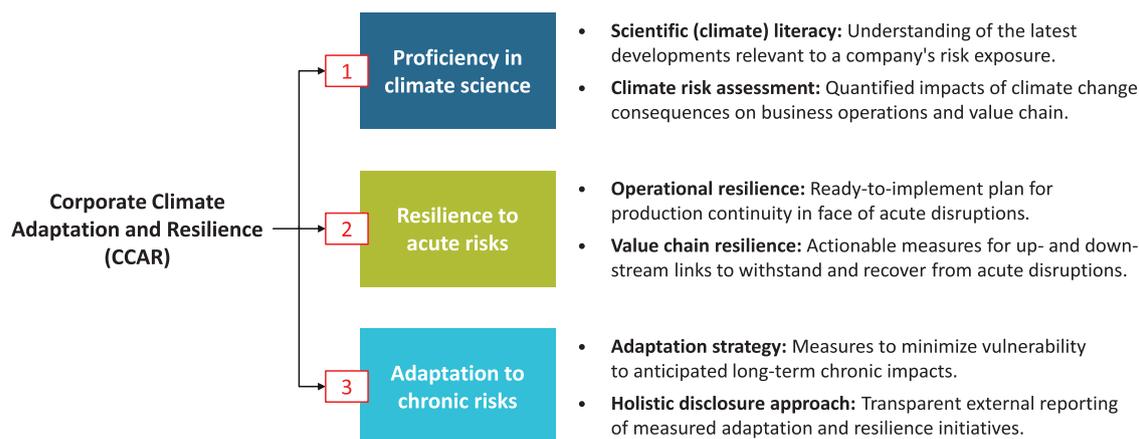
(2) In response to these drivers, corporates implement specific strategic or operational adaptation and resilience levers. Approximately half of the underlying papers (53%) showcase strategic initiatives like climate risk measurement and monitoring<sup>24,31,44,54–56</sup> or building cross-company adaptation networks<sup>52,57,58</sup>. They also highlight strategic compensation for business interruption or cash flow shortfalls due to physical hazards. Examples thereof are financial mechanisms such as weather<sup>34,53,59,60</sup> or climate change news<sup>61</sup> hedging. Adjusted leverage structures<sup>62–64</sup>, cash holdings<sup>65</sup> or loss provisions<sup>66</sup> also aim to mitigate these physical impacts. From a decision-making perspective, statistical approaches to incorporate adaptation considerations into pricing<sup>67,68</sup> and investment<sup>69</sup> are on the rise. Further operational dimensions (35%) can be adjustments to supply chains or production processes<sup>57,70</sup> in terms of, e.g., flexibilisation of inputs or logistics chains<sup>15,71,72</sup>, fortification of infrastructure<sup>14</sup> or even relocation thereof<sup>69,73</sup>. All of the above changes for long-term adaptation should, in theory, be mirrored by resilience levers that corporates employ to address sudden climate events. However, our analysis reveals that only a minor proportion of the literature (11%) touches upon acute disaster recovery measures like emergency response and disaster relief plans<sup>16,24,48</sup>. This limited acute resilience focus raises concerns, particularly given the ongoing occurrence of extreme weather events<sup>1</sup>. Failing to develop effective countermeasures exposes corporates to multiple risks like disrupted input logistics, damaged production sites and consequently financial losses<sup>14,59,73</sup>. Ultimately leading to bigger systemic impacts, this threatens the financial stability across a variety of sectors and economies<sup>51</sup>.

### Regulatory and reporting influences

In recognition of these emerging global risks, regulators and standard-setters are increasingly demanding transparency in how companies assess and respond to them<sup>74</sup>. A variety of reporting standards have now emerged to facilitate this: voluntary ones companies choose to implement such as the Global Reporting Initiative (GRI) or the Carbon Disclosure Project (CDP); nationally adapted ones as in the state of California<sup>75</sup> based on, e.g., the Task Force on Climate-related Financial Disclosures (TCFD) or the Standards 1 and 2 of the International Sustainability Standards Board (ISSB)<sup>76</sup>; or legally mandated cross-country ones such as the European Sustainability Reporting Standards (ESRS) 1 and 2. Amidst the need for comparability between various disclosures and expanding regulatory demands<sup>77</sup>, climate risk reporting standards are beginning to converge, as evidenced by the recent shift of TCFD monitoring responsibilities to the ISSB<sup>78</sup>. In this evolving regulatory landscape, disclosure is becoming increasingly pertinent to corporates. More specifically, various states have already initiated legislative processes (e.g., California<sup>75</sup>, EU<sup>27</sup>, New Zealand<sup>79</sup>, UK<sup>26</sup>), or have announced to do so recently (e.g., US SEC<sup>80,81</sup>). As these come into force, companies will be legally obliged to focus on the impact of physical risks on their financials or beyond, depending on, e.g., size or operational boundaries. In this respect, the EU's ESRS, starting in 2024, stands out as one of the most advanced<sup>76</sup> in terms of an internationally agreed, legally binding reporting standard that investigates not only financial but also the impact materiality of physical climate risks<sup>82</sup>.

### Creating transparency on the concept of climate adaptation for private sector organisations

Blending the systematic literature review with the regulatory insights presented above, we understand that distinct factors drive corporate adaptation, and, in response, organisations employ specific measures. Despite rising academic attention to CCAR due to noticeable climate extremes and increased concern from countries and regulators, there remains confusion in the public discourse about the nature of adaptation and resilience for



**Fig. 2 | Typology of key CCAR elements.** Figure 2 outlines the three key elements that need to be incorporated into a strategy to address physical climate risks. For clarity in the following business adaptation framework (see Fig. 3), each component

is distinctly colour-coded. In this context, the adjectives 'short-term' and 'acute' are used interchangeably. The same applies to 'long-term' and 'chronic'.

businesses. This is not surprising, as, to date, the reporting suggestions can be imprecise<sup>83</sup> and there is no succinct definition of CCAR on the firm-level<sup>14</sup>, leaving considerable ambiguity. Consequently, we usually do not see corporates with a clearly defined action plan for both acute (short-term) and chronic (long-term) climate impacts yet<sup>84</sup>—generally speaking, there is limited clarity on where the private sector stands<sup>85</sup>. This uncertainty calls into question its comprehension of climate risk disclosure standards like TCFD or ESRS and the sincerity of its ambition and ability to tackle these impacts today and in the future<sup>50</sup>. Acknowledging the complexity of the adaptation action and regulation landscape underscores the need for a common CCAR understanding to accelerate its momentum.

To build this foundational understanding, it is essential to define a universally applicable typology as a frame of reference that outlines the fundamental elements of firms' adaptation and resilience efforts. It is critical that these are clarified so that they are comprehensible to every firm before they begin to engage in or report on CCAR. Derived from our review and the key notions of climate risk regulation, we conceptualise a triad of overarching elements (Fig. 2). Convinced that these are integral to a comprehensive CCAR strategy, we propose the following: (1) Well-researched scientific knowledge and risk assessments present the basis of any climate-related strategy, i.e., 'Climate proficiency' is key. On this base, (2) acute, short-term climate impacts must be urgently confronted, i.e., 'Resilience to acute risks', while (3) chronic, long-term changes need to be prepared for, i.e., 'Adaptation to chronic risks'. This triad stems from seeing a focus on time- and physical-risk-oriented movements in our systematic literature review—one toward short-term natural disasters and the other toward long-term adaptation planning.

### Climate proficiency

'Climate proficiency' presents the initial element of this holistic CCAR typology. It is grounded in our learning that managerial perception of climate change and a company's exposure to its risks are significant determinants of adaptation<sup>22,39–43</sup>. Given the clear importance of awareness as a base, companies need to enable and upskill their staff<sup>50</sup>. Thus, this first element encompasses integrating climate science as key knowledge for a firm to be able to conduct thorough climate risk assessments. As such, scientific (climate) literacy implies an up-to-date understanding of current climate and regulatory developments. Spreading these insights develops managerial awareness and perception of this cause's urgency. Any company aiming for high literacy should thus regularly monitor the latest science<sup>50</sup>, e.g., provided by the IPCC, to update its risk exposures according to changes in predictions<sup>13,86,87</sup>. Ultimately, this supports the process of identifying and quantifying acute and chronic impacts on a company's operations along its value chain<sup>3,31,56,88</sup>.

### Resilience to acute risks

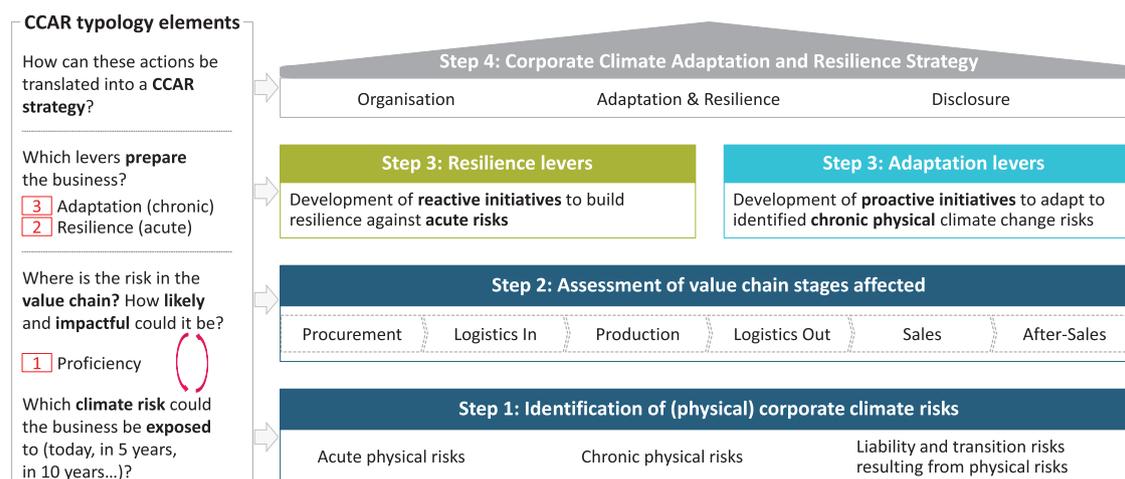
Engaging in fast risk management today is especially relevant for short-term, unpredictable events like sudden hurricanes or wildfires<sup>1,89</sup>. Consequently, the second element of the CCAR typology is 'Resilience to acute risks'. It draws on the literature highlighting how climate risks affect business operations<sup>31–35</sup>, and how embeddedness in networks and value chains<sup>52,53</sup> can assist in responding to these immediate shocks. As such, this second element encapsulates both the operational and value chain strength required to deal with sudden physical impacts. Operational resilience refers to the imperative to have a ready-to-implement plan to assure production continuity and maintain essential functions in the face of all types of extreme weather events<sup>15,24,90</sup>. As an enabler thereof, simultaneous value chain resilience is of the essence. This is equally critical, as reflected in the literature discussing modifications of the supply chain<sup>15,71,72</sup>. It suggests resilience measures such as supplier choice or transportation flexibility to withstand or recover from such short-term disruptions<sup>52</sup>.

### Adaptation to chronic risks

Simultaneously, responses to chronic risks like rising temperatures or changes in precipitation need to be developed<sup>1</sup>. Thus, underpinned by the CCAR literature's focus on long-term strategic<sup>59,73</sup>, financial<sup>34,53,59,60</sup> or company-internal adjustments<sup>56,58,70,91–94</sup>, the last element of this holistic CCAR typology is 'Adaptation to chronic risks'. Based on identified future vulnerabilities, strategically adaptive measures can be delineated and planned accordingly. In line with the foreseeability of such chronic impacts, this element also links to the anticipated regulatory landscape for climate risks<sup>95</sup>. Currently under development and already mandatory in some countries, companies will soon be required to acknowledge the potential (non-) financial impacts on their business and disclose their corresponding risk mitigation strategies<sup>74</sup>. They therefore need to adjust internal reporting mechanisms<sup>95</sup> to take account of these new measurements<sup>55</sup> and to disclose them externally<sup>47</sup>.

### Operationalising a practical business adaptation and resilience framework

Following this definition of the CCAR typology, we now turn to the question: How does a company operationalise these elements to navigate toward a climate-adapted and -resilient way of doing business? Grounded in our analyses, we answer this question by delineating a practical business adaptation framework. As such, it aims to bridge the gap between the private sector's current and aspirational, climate-adapted state, which should be disclosed to regulatory bodies (Fig. 3). It is a practical tool that firms can leverage to get an overview on which first steps to take toward a thorough CCAR strategy. As a step-by-step process, the business adaptation



**Fig. 3 | Business adaptation framework.** This figure presents a practical application of the CCAR typology elements (see Fig. 2), transforming them into actionable steps within the business adaptation framework. On the left side, pivotal questions corresponding to the three typology elements prompt strategic considerations for each

operational step of the framework, which is illustrated on the right. The colour-coding establishes a visual link between each step of the framework and its respective element within the CCAR typology.

framework operates through a question series and starts by building a baseline to review the status quo. Key actions for adaptation and resilience are identified. Ultimately, these form part of a publicly disclosed CCAR strategy that is integrated into a firm’s business strategy.

**Step 1: Setting a CCAR foundation by identifying climate risks and their impact**

Initially, the business adaptation framework directly links to the CCAR typology’s first element—‘Climate proficiency’. Its subdimensions (*scientific literacy* and *risk assessment*) present the starting point for identifying and categorising climate risks. These can be either physical (acute and chronic) or liability and transition-related consequences of physical risks<sup>24,94</sup>. Depending on the jurisdiction in which a company operates, it could use the global TCFD guidelines as a working basis for this first step—many countries and regional governments also provide useful local climate risk assessments. Having assessed which climate risks the business is exposed to along the value chain from procurement to sales<sup>31,56,88</sup>, these should be further analysed to rank them according to their likelihood of occurrence under different global warming scenarios. For instance, the Network for Greening the Financial System’s ‘Scenarios Portal’ could be leveraged for a global overview<sup>96</sup>. This prioritisation exercise should be carried out for varying timeframes<sup>56</sup>—i.e., what are the key climate risks today, in 10, 15 and 20 years’ time? Communicating these evaluations internally enables corporates to build the foundational knowledge, i.e., the *scientific literacy* and *risk assessment*, necessary to fully operationalise element 1.

**Step 2: Building acute climate resilience operationally and along the supply chain**

Having identified the base (where, how, and when climate risks are likely to occur), the business adaptation framework’s next step draws the connection to the second element ‘Resilience to acute risks’. Corporates increasingly realise that not all climate risks can be foreseen and mitigated pre-emptively, as some impacts happen suddenly and without warning. Referring to both subdimensions of element 2, companies must develop short-term resilience levers to have the capability to react immediately upon acute physical impact<sup>15,97</sup>. These levers aim at both their own operations as well as aspects up and down their supply chain. For instance, rapid response mechanisms could include establishing a climate disaster task force, implementing emergency operations plans, or even storing slack inventory<sup>15,16,97</sup>. Beyond that, companies could also investigate parametric vs. indemnity arrangements with their insurers to cover potential losses due to acute impacts<sup>98</sup>.

**Step 3: Developing strategic adaptation initiatives for chronic impacts**

As climate science clearly shows that long-term chronic impacts are coming, there is immense value for companies to be proactive in addressing these. While element 2 is about creating reactive, short-term measures to face acute risks, element 3 dives into proactive, long-term levers to address chronic impacts. Thus, the business adaptation framework’s third step focuses on developing adaptation actions that enable businesses to mitigate these. Firms need to think strategically and initiate such adaptation<sup>14,40</sup> early to implement countermeasures for foreseeable climate change impacts<sup>91</sup>. Operational tactics may include modified production processes, locations or fortification of infrastructure. From a more strategic perspective, corporates could explore new markets and products, or financially hedge chronic risks such as changed precipitation or temperature patterns with, e.g., weather derivatives<sup>34,53</sup>.

**Step 4: Integrating CCAR with business strategy and disclosure requirements**

The final step operationalises the last part of the CCAR typology’s third element by preparing the adaptation and resilience efforts for integration into the business strategy and disclosure to external stakeholders. In this step, corporates first translate the CCAR strategy into concrete initiatives and targets, covering both long-term adaptations and short-term reactivity. To implement these in the business strategy<sup>92,99,100</sup>, companies could set up cross-functional teams that hold responsibility for aligning stakeholders in the implementation of these levers and ensuring that they are considered in budgeting decisions. They also need to introduce climate risk assessments into routine business operations, aligning CCAR goals with business objectives. Ultimately, to evaluate the levers’ success, established evaluation processes should track both initiative progress and effectiveness using pre-defined key performance indicators. Leveraging the latter, companies can complement their existing disclosures by reporting on material climate risks and their plans to address them.

**Discussion**

While this paper develops a CCAR typology and an operationalisation thereof as a practical business adaptation framework, our work also uncovers a noticeable shortfall of research probing the outcomes and performance of these initiatives, i.e., measuring CCAR success in terms of financial, market or societal benefits. Just a tenth of the reviewed literature delves into financial outcomes of adaptive actions (11%)<sup>31,59,60,99</sup>—even fewer studies investigate consequences such as keeping up the status quo (6%)<sup>59,101</sup>,

## Box 1 | Crucial research pathways for CCAR academics

### 1. Improve measurement of climate risk exposure across industries

Based on our review, we conclude that if existing research sets a focus, it is on manufacturing sectors<sup>49,88,93,102</sup> rather than physical climate risks. The extent of these risks' impacts varies strongly depending on the assessment tool in question<sup>105</sup>. This is why their key takeaways should be taken cautiously when generalising to differing industries or when comparing one score<sup>105</sup> or rating<sup>8</sup> to another, as they use varying methodologies, input data and climate scenarios<sup>74</sup>. Thus, a globally agreed-upon and consistent methodology to measure these physical risks is needed. If this is not developed, policymakers and industry bodies may establish CCAR incentives of which the effectiveness would be limited or potentially even detrimental due to misleading industry- or risk-specific insights.

### 2. Build theorising on outcomes of CCAR initiatives

Currently, we do not know much about or measure whether corporates' pilot adaptation and resilience levers prove to be successful when climate risks strike<sup>13,86</sup>. Only very few papers theorise and investigate how, e.g., financial hedging may lead to more stable financial outcomes for corporates<sup>34,53,59,60</sup>. However, this financial perspective is only one of many outcomes of adaptation and resilience initiatives. Others could be, e.g., potential for technological innovation<sup>14</sup>, cross-company partnerships<sup>71</sup> or cooperations with the public sector<sup>14</sup>. To assess these opportunities, theory is needed that dives into levers and their potential outcomes. Only then can we test this 'black box' and assess whether current assumptions about the effectiveness of initiatives are correct or need improvement.

### 3. Develop quantitative measurements to assess corporates' extent of CCAR engagement

Building on the above, approaches to measuring CCAR implementation are currently limited with only a few approximations<sup>87,107,108</sup>. Ultimately, this makes it difficult to assess the progress and outcomes of firms' adaptation. The definition of standardised performance indicators to capture the extent of corporate CCAR engagement is therefore crucial. Only when a measurement base is established will it be possible to highlight best practices and inform policymakers. Such a standardised perspective could be put forward by a consortium of regulatory bodies, overlooking a variety of climate risk disclosure approaches. This would also be useful for comparing future disclosures by firms which, given the

current state of regulation, do not seem to have a clear method for doing so<sup>84</sup>. In light of these considerations, the role of company-internal accounting and reporting departments will become increasingly important in developing and/or reporting these standardised CCAR indicators<sup>55</sup>.

### 4. Assess opportunities of public-private partnerships

As the private sector faces complex changes, it might seek external support to tackle these. Cooperations like public-private partnerships have the potential to advance topics that surpass the capacity of any single actor<sup>109,110</sup>. As one of these topics, CCAR promises to be an interesting partnership area. Combining the strengths of public and private actors could create a robust platform for innovation and solutions, as exemplified by the Green Climate Fund<sup>111</sup>. An in-depth examination could look at how resources should be pooled to drive adaptation and what public incentives could kickstart CCAR initiatives. Diving into this will yield crucial insights for both policy and practice.

### 5. Encompass the Global South to develop a CCAR understanding across diverging regions

Predominantly stemming from the Global North, CCAR research does not provide a global picture. It is widely known that climate change disproportionately affects the Global South<sup>1</sup>; their private sectors face different challenges than peers in the Global North. Among such hurdles, limited institutional or regulatory support can hinder this transition<sup>112,113</sup>. Current CCAR work in economics and management neglects to address these regions, limiting the development of geography-specific adaptation pathways. Cross-regional studies could solve this and provide an inclusive overview.

### 6. Expand the knowledge of climate risks' true cost

An initial understanding of the overall economic costs of climate-related events has been developed<sup>114,115</sup>. Still, it is limited by a lack of precision on the sectoral level. Overlooking the specific cost and benefit implications for particular industries is dangerous, as the true cost of non-adaptation cannot be established<sup>13,14</sup>. Only this knowledge can adequately inform strategic decisions and help prioritise investments—both from a public and private sector lens. Addressing this, interdisciplinary research should involve economics and management, environmental, and risk science. Pilot case studies could explore these costs in-depth, ultimately enabling the development of effective CCAR strategies across sectors.

reputation or even innovation opportunities (5% each)<sup>88,102–104</sup>. This limited outcome-oriented exploration underlines the scarcity of attention paid to actual CCAR measurement. Without robust measurement of a lever's success, its long-term viability and efficacy remain unproven. Hence, it is unclear whether the strategic or operational levers hold when faced with increasing climate risks. As the stakes of maladaptating are high, these knowledge gaps constitute essential areas for future investigation.

Intriguingly, the emphasis of CCAR research seems to be solely on nature-based risks, as a significant proportion of the papers analysed (79%) concentrate on physical impacts. In contrast, only a minority also dive into regulatory and liability (29%) or financial and transition risks (33%). Academics' high focus on physical aspects is interesting considering that some businesses may perceive regulatory ones as the most critical<sup>92,100</sup>. It showcases a discrepancy between researchers and the private sector's perception of the risks posed by the climate crisis. This misalignment could also be due to the so-called 'tragedy of the horizon', as companies and managers may have a shorter-term focus on what is most relevant<sup>5</sup> than academics. In line with their focus on physical risks, a number of tools have been developed to assess companies' exposure to physical impacts<sup>105</sup>. Given the wide variation in the results of the assessments<sup>105</sup>, it is crucial to point out that the transition towards adaptation and resilience is a continuously evolving process for

both academics and practitioners<sup>14,106</sup>—it is by no means static or a one-time event. As a testament to the topic's dynamic nature<sup>52,56</sup>, evolving CCAR research could balance its focus with the private sector's practical concerns. For example, to better understand CCAR and its effectiveness, future work could develop standardised measures of industry risk exposure and examine the outcomes of efforts to adapt to these risks. The exploration of regulatory incentives as a complement to existing disclosure standards may also prove conducive to this transition. We elaborate on these pathways in Box 1 to encourage future scholarly inquiries.

## Conclusion

Our review of the most prominent business adaptation papers enabled us to develop a thorough understanding of the existing body of knowledge on corporate climate adaptation and resilience. We complemented this synthesis of the academic status quo with valuable regulatory insights to propose CCAR tools for corporates. Specifically, we contribute a firm-level typology of private sector adaptation and resilience to the academic discourse. It defines the crucial elements necessary for a corporate approach to physical climate risks. Exemplifying the urgency of addressing acute threats, planning for long-term chronic impacts, and the need for disclosure and integration across the organisation, this is particularly relevant for

businesses looking to begin their adaptation journey. For a practical perspective, we operationalised this typology into concrete steps by introducing the business adaptation framework. As a demonstration of the CCAR typology, it is designed as a globally applicable, step-by-step process to kickstart companies seeking to improve their climate resilience or that will soon be subject to disclosure requirements. Complementing regulatory standards, our framework helps businesses take the first steps to systematically assess risks and strategise countermeasures; thereby aiming to set a precedent for climate-adapted businesses.

Integrating theoretical knowledge and practical CCAR implications, we facilitate a nuanced understanding of what state of climate adaptation and resilience corporates should strive for. To develop this further, the systematic literature review allowed us to identify blindspots where future academic work is required. Highlighting these gaps, we aim to direct research towards areas that will best support private sector adaptation endeavours. As the climate crisis accelerates, the ability of corporates to adapt will be critical. This research should serve as a stepping stone, equipping businesses with a better understanding of how to navigate the complexities that lie ahead.

### Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

### Data availability

All articles included in this systematic literature review are available in the Supplementary Information. Further data that support the findings of this study will be made available upon reasonable request by the Corresponding Author.

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### Author contributions

K.H. conducted the analyses, developed the concepts and wrote the manuscript. D.B. and A.L. contributed with project administration, supervision and conceptual support. All authors approved the final version and assumed responsibility for the paper.

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The authors declare no competing interests.

### Additional information

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