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Financial effects of carbon risk and carbon disclosure: A review

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Abstract

Carbon risk has generated significant adverse impacts on firms, investors and other stakeholders. Carbon disclosure may provide market participants with information to effectively manage risks and explore opportunities. We conduct a critical review of the growing literature in these fields and seek to examine the financial effects of carbon risk and carbon disclosure. A total of 78 papers, published in influential accounting, finance, business, economics and management journals between 2011 and 2021, are reviewed. We categorise the financial effects into four groups: financial performance, valuation relevance, cost of capital and risk profiles (measures). The proxies for carbon risk and carbon disclosure are summarised. This review demonstrates inconclusive relationships between carbon risk (carbon disclosure) and firms' financial measures. These inconclusive findings may result from different carbon risk (carbon disclosure) measures, financial performance measures, sample geographies, sizes and periods, and model specifications. This review further identifies and highlights future research opportunities in relevant areas and calls for more research work to understand the influence of climate change on firms' value and activities.

KEYWORDS

carbon disclosure, carbon emission, carbon risk, cost of capital, financial performance, risk profile, valuation relevance

JEL CLASSIFICATION

G32, M41, Q56

1 | INTRODUCTION

Following the Kyoto Protocol and the Paris Agreement entering into force, climate change has increasingly received more attention.[1] With continuing greenhouse gas (GHG) emissions, the long-lasting effects of global warming on each component of the climate systems will ultimately impact humans and ecosystems (see IPCC, 2022). Some authors have suggested that climate change may lead to a 'new normal' with significant impacts due to anticipated changes in the environment (Linnenluecke et al., 2016; Schelling, 1992). To combat climate change, the Paris Agreement set up an ambitious goal to limit global warming to below 2°C (preferably to 1.5°C), compared to the pre-industrial level. To be successful in achieving this temperature goal in the long term, many countries have pledged to achieve net-zero carbon emissions, with some countries establishing targets and plans and developing adaptation strategies.

Researchers have also begun to explore the impact of carbon emissions (carbon risk)[2] and carbon disclosure on firms' financial performance, valuation and relevant risks. Carbon risk typically refers to the impact of unexpected changes on firm value and business risks during the transition to a low-carbon economy. In the transition process, businesses may be exposed to various risks, such as policy and legal, technology, market and reputation risks (Foerster et al., 2017; Herbohn et al., 2022; Millar et al., 2018; TCFD, 2017). These risks are denoted as transition risks or non-physical risks[3] and have become essential factors for a firm in analysing climate-related issues.

Businesses also face growing pressure from various stakeholder groups (e.g., investors, suppliers, customers and creditors) in disclosing their climate change-related carbon information (i.e., carbon disclosure). Some firms have established their carbon disclosure systems to report carbon performance-related historical and prospective information including strategies, actions and achievements in reducing emissions. At the same time, some carbon disclosure initiatives have been established (Hahn et al., 2015). The CDP (formerly the Carbon Disclosure Project), one of the most influential initiatives, set up a framework to help firms to report their GHG emissions and relevant strategies for emissions reduction. While in some instances carbon disclosure may be mandatory, it is, for the most part, voluntary, with no reporting standards on carbon information (Borghei, 2021; Hahn et al., 2015; Hrasky, 2012; Kolk et al., 2008).

To comprehensively understand the financial effects of carbon risk and disclosure, papers published since 2011 in journals ranked B and above released by the Australian Business Deans Council (ABDC) in 2019 are reviewed.[4] A total of 78 published papers from January 2011 to December 2021 are identified and categorised, of which 61 papers are related to carbon risk and 17 papers are associated with carbon disclosure.[5] Additionally, the breakdown of journal rankings for the published papers is found to be A*: 20 (26%), A: 49 (63%) and B: 9 (11%). Not surprisingly, papers in A-ranked journals are significantly dominant.

[1]The Kyoto Protocol and the Paris Agreement took effect on 16 February 2005 and 4 November 2016, respectively. More information can be found at https://unfccc.int/.

[2]In practice, various GHG emissions are converted to carbon dioxide equivalent (i.e., CO_2-e) according to their potential in leading to global warming. For simplicity, in our review, we use the terms, 'GHG emission', 'carbon emission' and 'carbon risk' interchangeably. Collectively, we define them as carbon risk, i.e., the carbon emission-related negative impact. In general, lower carbon emission is related to lower risk, and thus better carbon performance. Other carbon performance indicators (e.g., carbon intensity, carbon exposure, carbon dependency) can be also used (Hoffmann & Busch, 2008).

[3]Although carbon risk is popularly described as transition risk, it can be a physical risk, as a failure of effective decarbonisation can expose the business to risks from the physical impacts of extreme weather events in the long term (Foerster et al., 2017).

[4]The initial intent to review papers that were published after the Kyoto Protocol took effect on 16 February 2005, is hampered by a lack of relevant publications between 2005 and 2010. Therefore, our review begins with papers from 2011, consistent with Velte et al. (2020). Justification can be found in Section 2.1.

[5]Velte et al. (2020) collect a total of 35 published papers associated with the impact of carbon risk or carbon disclosure on financial consequences, of which six papers are published in journals that are not ranked B or above of ABDC 2019, or that are not in the list of ABDC 2019. The number of papers in our review is significantly greater than that of Velte et al. (2020), as our sample period is more current and we include papers that use various measures of carbon risk.

Our review contributes to the literature in three respects. First, it significantly complements several extant review papers related to carbon risk and disclosure (e.g., Borghei, 2021; Velte et al., 2020). Our study is distinguished from Velte et al. (2020) and Borghei (2021) in that we focus on reviewing papers published in high-quality journals (ranking B and above of ABDC 2019), consistent with Habib et al. (2018) and He et al. (2021). Moreover, when compared with Velte et al. (2020), which examine published papers up to July 2019,[6] our review extends to December 2021. We find that a significant number of papers examining the financial effects of carbon risk and carbon disclosure have been published over the most recent 2 years, with an increase of approximately 114%.[7] Additionally, the study by Borghei (2021) focuses on only carbon disclosure, but our review covers both carbon emissions (or carbon risk) and carbon disclosure.

Most importantly, aside from the cost of capital (cost of debt or cost of equity), normally considered one type of firm risk, we collect and review papers that explore the effect of carbon risk and carbon disclosure on other relevant risk measures of firms.[8] While the cost of capital is important in valuing a firm by discounting future cash flows, other types of risk, such as default risk (or credit risk) and downside risk, are critical in influencing business success. In line with Gillan et al. (2021), we also use 'risk profiles (measures)' representing other types of risk to distinguish from 'the cost of capital'.

Second, we identify and categorise carbon risk measures. In the extant literature, carbon risk generally describes the adverse impact of carbon emissions and is measured using various definitions. In this review, carbon risk measures are summarised using four proxies. The first proxy for carbon risk is the absolute amount (level) of carbon emissions or any kind of difference in carbon emissions (e.g., Bolton & Kacperczyk, 2021; Chakrabarty & Wang, 2013; Gallego-Álvarez et al., 2015). The level of or difference in carbon emissions is the most straightforward proxy for carbon risk.

The second proxy is carbon intensity (or carbon emission intensity), which is normally calculated by scaling carbon emissions using a firm's particular financial statement item, e.g., assets or sales (e.g., Kabir et al., 2021; Kim et al., 2015; Trumpp & Guenther, 2017). The purpose of using scaled carbon emissions is to control the effect of the firm size or certain activities. The third proxy is based on climate change-related events. This proxy likely captures relevant policy or regulatory risks a firm is exposed to, as most events indicate new policies in place or changes in the existing policy. These policy changes require businesses to adjust and improve their strategies to ensure regulatory compliance (e.g., Herbohn et al., 2019; Neudorfer, 2021; Nguyen & Phan, 2020). The fourth and final proxy is related to carbon emission scores or carbon performance ratings (Ganda, 2018; Qian et al., 2020; Zhou, Zhang, et al., 2018). A carbon emission score reflects a firm's commitment and effectiveness in reducing emissions, and the carbon performance rating focuses on a firm's climate change awareness, and mitigation and adaptation strategies.

The identification of proxies for carbon risk helps understand and explain findings, especially when inconclusive. Although many other factors could have led to inconclusive results, the different measures (proxies) relating to carbon risk provide alternative justifications (Busch & Lewandowski, 2018; Yagi & Managi, 2018). If the term 'carbon risk' is used as a generalisation

[6]July 2019 is referred to the submission time of Velte et al. (2020).

[7]Twenty-nine papers published in journals ranked B and above of the ABDC 2019 are reviewed in Velte et al. (2020). This number increases by 114% (33/29 = 114%) during 2020–2021, and represents 42% (33/78 = 42%) of the total number of our reviewed papers.

[8]Although the cost of capital (both debt and equity) is one measure of risk, we separate the cost of capital from other risk measures (e.g., default risk, tail risk) in our review. This separation is consistent with Gillan et al. (2021), who use two sub-sections describing risk measures and the cost of capital, respectively. In their section 5.1 'Risk measures', Gillan et al. (2021) discuss systematic risk, credit risk/ratings, default risk, downside risk, and so on; in Section 5.2 'Cost of capital', they discuss the cost of debt and the cost of equity. All these types of risk might ultimately affect the cost of capital of a firm, whereas the separation provides us with a clearer view of how carbon risk impacts a firm's other risks. In this review, other risks are denoted as 'risk profiles (measures)'.

to describe the relationships, a more accurate explanation may be overlooked to more correctly assess these inconclusive findings.

Finally, through our review, we propose several potential research directions that may become increasingly important. (1) Research about derivatives markets is worthwhile. A large number of our reviewed studies are associated with the stock and debt markets. While several published papers examine the effect of carbon risk and disclosure relating to options markets, it is expected that more research into derivatives markets may occur. The reason is that derivatives markets would provide investors with a rich source of information for their investment and risk management (Ilhan et al., 2021; Pérignon & Villa, 2002). (2) How carbon risk and disclosure affect the risk profiles of a firm has not been extensively examined. Kabir et al. (2021) and Ilhan et al. (2021) investigate the impact of carbon risk on firms' default risk and tail risk, respectively. Other types of risk, such as liquidity risk, supply chain risk and crash risk may also require investigation.[9] These risks could be critical in evaluating the value and/or sustainability of firms (Gillan et al., 2021). (3) Our reviewed studies analyse carbon risk and disclosure and their effects on a firm's financial prospects. The more important research work may be to explore the determinants that could be used to enforce (mitigate) the good (bad) relationships between carbon risk and financial consequences. Velte et al. (2020) analyse some aspects of governance, whereas other determining factors are also worth further exploration. For example, corporate governance reform can promote investors' and managers' carbon risk awareness, which may accelerate or reduce the effect of corporate governance (Luo & Tang, 2021). (4) Capital markets value carbon disclosure, so more studies on carbon information disclosure are required. With the release of the recommendations of the Task Force on Climate-Related Financial Disclosures (TCFD) by the Financial Stability Board in 2017, integrating relevant recommendations and carbon disclosure is a promising research direction.

We organise the rest of our review as follows. The research methodology, descriptive summary and historical co-citations are presented in Section 2. Section 3 describes the measures of carbon risk and carbon disclosure. Section 4 analyses empirical findings of the financial effects of carbon risk and carbon disclosure. Section 5 provides conclusions and future research.

2 | RESEARCH METHODOLOGY, DESCRIPTIVE SUMMARY AND HISTORICAL CO-CITATIONS

2.1 | Research methodology

We search relevant literature, focusing on three database resources: Web of Science (WoS), ScienceDirect and Google Scholar by following several recent review papers relating to climate change and carbon risk and disclosure, such as Velte et al. (2020), Borghei (2021) and He et al. (2021). We also follow these papers to select keywords. We further categorise the keywords into two groups (He et al., 2021). The first group of keywords are related to carbon and climate change: climate change, greenhouse gas emission*, GHG emission*, carbon emission*, carbon intensity, carbon efficiency, carbon risk and carbon disclos*. Those in the second group are associated with financial consequences: financial performance, financial profitability, valu* relevance, cost of capital, cost of debt, cost of equity and firm risk. Our search string includes the combination of keywords from the two keyword groups. For example, in the WoS database, the keyword combination is: TS = (‘climate change’ OR ‘greenhouse gas emission*’ OR ‘GHG emission*’ OR ‘carbon emission*’ OR ‘carbon intensity’ OR ‘carbon efficiency’ OR ‘carbon risk’ OR ‘carbon

[9]For example, see Crouhy et al. (2000) for credit risk, Ho et al. (2015) for supply-chain risk, and Habib et al. (2018) for stock price crash risk. A research work by Bose, Lim, et al. (2021) concerning the impact of carbon risk on stock price crash risk was not available for assessment when this review paper was written.

disclos*') AND TS = ('financial performance' OR 'financial profitability' OR 'valu* relevance' OR 'cost of capital' OR 'cost of debt' OR 'cost of equity' OR 'firm risk'), where the asterisk (*) is used as a wildcard to identify similar words with varying forms (for example, valu* could be 'value' or 'valuation'). We follow Borghei (2021) to use the Social Sciences Citation Index (SSCI) and the Science Citation Index Expanded (SCI-EXPANDED) databases and include English language papers that are published in the area of business economics. Next, we ensure that any of this combination of these keywords is included in the title or keyword list of the paper. If not, we integrate the abstract of the paper to assess its relevance and exclude the papers that do not meet these criteria.[10] Our examination requires that the selected papers should be published in journals ranked B and above listed in the ABDC 2019 to ensure the reviewed papers' quality (Habib et al., 2018; He et al., 2021). We do not review working papers because (i) the papers may not be vetted by the review process; (ii) some working papers may not be identified, resulting in selection bias (Habib et al., 2018).

We further perform a cited reference search after using the above literature search filters to include potentially relevant papers that have not been included through the initial search (Borghei, 2021). As a result, 10 relevant papers are identified through backward/forward citation searches and are presented in Table 1. These papers are manually added to the final dataset. Finally, we review the collected papers, extract relevant information and present them in Section 4.

We initially intend to review papers published after the Kyoto Protocol took effect on 16 February 2005, as it is one of the important milestones concerning the reduction of GHG emissions to tackle global warming. Following this, interest by governments, businesses, investors and academic researchers in climate change and its impacts, and relevant strategies to mitigate and adapt to global warming has increased significantly.

In our final literature dataset, we find no relevant publications between 2005 and 2010, hence our review date begins in 2011 with the final sample including 78 papers published in 39 journals up until December 2021.

2.2 | Descriptive summary

The list of 39 journals examined in this study is shown in Table 2, in which the journals are categorised by the ranking of ABDC 2019. The number of journals with the rank of A*, A, and B

TABLE 1 Papers added manually to the dataset.

No.	Author(s) and year	Journal
1	Aggarwal and Dow (2012)	*The European Journal of Finance*
2	Alsaifi et al. (2020b)	*Journal of Cleaner Production*
3	Chakrabarty and Wang (2013)	*Thunderbird International Business Review*
4	Fujii et al. (2013)	*Business Strategy and the Environment*
5	Gallego-Álvarez et al. (2015)	*Journal of Cleaner Production*
6	Kim et al. (2015)	*Journal of Cleaner Production*
7	Lannelongue et al. (2015)	*Business Strategy and the Environment*
8	Nishitani and Kokubu (2012)	*Business Strategy and the Environment*
9	Schiemann and Sakhel (2019)	*European Accounting Review*
10	Zhou, Zhou, et al. (2018)	*Emerging Markets Finance and Trade*

[10]For some papers, an examination of the full text might be required to assess relevance to our review.

TABLE 2 List of journals of the reviewed publications.

No.	Journal	Journal ranking	No. of papers reviewed	Total (percentage)
1	*British Accounting Review*	A*	3	
2	*Contemporary Accounting Research*	A*	1	
3	*Energy Economics*	A*	3	
4	*European Accounting Review*	A*	2	
5	*Journal of Banking and Finance*	A*	3	
6	*Journal of Business Finance and Accounting*	A*	1	
7	*Journal of Corporate Finance*	A*	3	
8	*Journal of Financial Economics*	A*	1	
9	*Review of Accounting Studies*	A*	1	
10	*Review of Financial Studies*	A*	1	
11	*The Accounting Review*	A*	1	20 (26%)
12	*Abacus*	A	1	
13	*Accounting and Finance*	A	2	
14	*Australian Journal of Management*	A	2	
15	*Business and Society*	A	1	
16	*Business Strategy and the Environment*	A	17	
17	*Ecological Economics*	A	4	
18	*Economic Modelling*	A	1	
19	*Economics Letters*	A	1	
20	*Environmental and Resource Economics*	A	1	
21	*International Journal of Production Economics*	A	1	
22	*International Review of Financial Analysis*	A	2	
23	*Journal of Accounting and Public Policy*	A	2	
24	*Journal of Business Ethics*	A	2	
25	*Journal of Cleaner Production*	A	5	
26	*Journal of Contemporary Accounting and Economics*	A	1	
27	*Journal of Environmental Management*	A	1	
28	*Organization and Environment*	A	2	
29	*Pacific-Basin Finance Journal*	A	1	
30	*The BE Journal of Economic Analysis and Policy*	A	1	
31	*The European Journal of Finance*	A	1	49 (63%)
32	*Accounting Forum*	B	1	
33	*China Journal of Accounting Studies*	B	1	
34	*Emerging Markets Finance and Trade*	B	1	
35	*Pacific Accounting Review*	B	1	
36	*Review of Accounting and Finance*	B	1	
37	*Social Responsibility Journal*	B	1	
38	*Sustainability Accounting, Management and Policy Journal*	B	2	
39	*Thunderbird International Business Review*	B	1	9 (11%)
	Total		78	78 (100%)

is 11, 20, and 8, respectively. As expected, A-ranked journals are in the majority. The number of papers included in each journal is also shown. Of the 78 papers examined, 20 papers are from A* journals, while A and B journals generate 49 and 9 papers, respectively, with a corresponding percentage of 26%, 63% and 11%. On average, two (78/39) papers are published in each journal. For the ranking groups, the average number of papers is 1.81 (20/11), 2.45 (49/20) and 1.13 (9/8) in the A*, A and B groups, respectively.

Table 3 demonstrates the yearly distribution of reviewed papers for the period 2011–2021, and Figure 1 visualises this distribution and shows the cumulative publications. The total number of reviewed papers increases from 2011 to 2015; however, surprisingly the number of papers decreases sharply over 2016–2017 with no relevant publications in 2016, while in 2018 the publications resume. We conjecture that this may be related to the Paris Agreement announcement at the end of 2015. Researchers attempt to comprehensively explore the response of financial markets and investors to the Paris Agreement on climate change, which results in lower publication numbers in the following 2 years. While the publications experience another sharp drop in

TABLE 3 Yearly distribution of publications for the period 2011–2021.

	Carbon risk						
Year	Financial performance	Valuation relevance	Cost of capital	Risk profile	Sub-total	Carbon disclosure	Total
2011	2				2	1	3
2012	4				4		4
2013	2	1			3	2	5
2014	2	1	1		4	2	6
2015	5	2	1		8		8
2016							
2017	2	2			4	1	5
2018	5	1	2		8	2	10
2019		1			1	3	4
2020	4	2	3	2	11	2	13
2021	1	6	4	5	16	4	20
Total	27	16	11	7	61	17	78

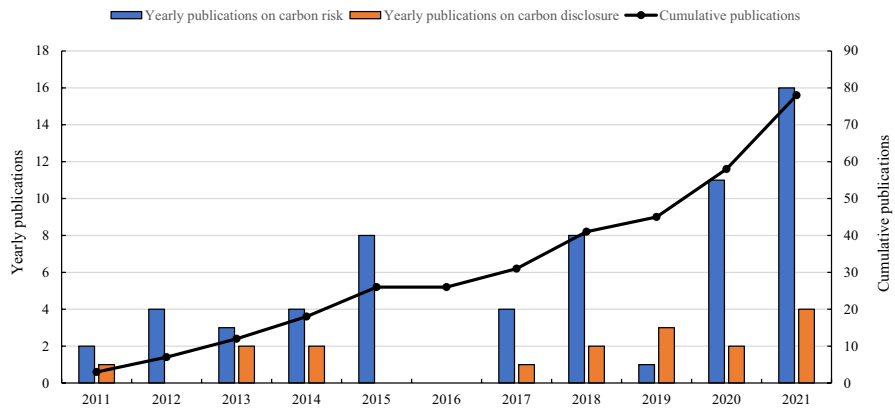

FIGURE 1 Yearly distribution of publications and cumulative publications for the period 2011–2021.

2019, in the most recent 2 years (i.e., 2020 and 2021), the highest yearly publications (i.e., 13 and 20 publications) over the sample period have been found.

We categorise each paper into carbon risk and carbon disclosure groups according to the focus of each paper on carbon risk or carbon disclosure. Of the total of 78 papers, 61 papers are related to carbon risk and 17 papers are associated with carbon disclosure. In the carbon risk group, we further classify the papers into four sub-groups determined by different financial effects of carbon risk: financial performance, valuation relevance, cost of capital and risk profiles (e.g., default risk, tail risk). We observe that close to half of the studies (27 out of 61) explore the effect on financial performance. The numbers of studies on valuation relevance, the cost of capital and risk measures are 16, 11 and 7, respectively. In the carbon disclosure group, the number of studies is much lower compared to that of the carbon risk group so further classification into sub-groups of financial effects is not necessary. Since 2018 the number of studies investigating the financial impact of carbon disclosure is very stable. As a result, the total number of our reviewed studies related to the financial consequences of carbon risk and carbon disclosure steadily incline over the past years (except 2019), a trend we expect to continue.

2.3 | Historical co-citations

To analyse the influence of reviewed papers in our collection, we extract their historical co-citations using *HistCite*™ software.[11] Here, we retain only the papers that are cited at least once by other reviewed paper(s); that is, the citation cut-off with the Local Citation Score (LCS), representing each paper's citation count, is one (i.e., LCS ≥ 1). Table 4 shows the citation details.

We observe that the paper by Matsumura et al. (2014) has the highest citations (LCS = 28), indicating it is the most influential paper in our reviewed paper dataset. Several other highly cited papers include Chapple et al. (2013), Clarkson et al. (2015), Griffin et al. (2017), Busch and Hoffmann (2011) and Jung et al. (2018), with an LCS value of 22, 21, 17, 14 and 14, respectively. Five of these six papers focus on carbon risk,[12] suggesting that the financial effect of carbon risk has been more broadly examined than that of carbon disclosure (Hahn et al., 2015). This is consistent with our findings that over 50% of our reviewed studies on carbon disclosure have been conducted since 2019, so they have a lower number of citations. The increased attention to carbon disclosure in the most recent 2 years is closely related to concerns about the impact of climate change. For example, the recommendations of the TCFD emphasise the reporting of climate-related information and have been adopted by many countries and organisations (Herbohn et al., 2022).[13]

Of the six studies, four are related to value relevance (Chapple et al., 2013; Clarkson et al., 2015; Griffin et al., 2017; Matsumura et al., 2014). Our review also shows a significant increase in the number of studies on firm valuation in 2021. This suggests that value creation is one of the key research topics by incorporating environmental factors, such as carbon emissions. Moreover, the key authors of three papers are from Australia (Chapple et al., 2013; Clarkson et al., 2015; Jung et al., 2018). Australian carbon-intensive industries play a dominant role in economic development, but they have been strongly criticised for their pollution. This may be the reason why Australia is the country with greater awareness of environmental responsibility (Nguyen, 2018), and its researchers have paid a high level of attention and contributed their research efforts to environmental issues.

[11]The citation data from the WoS database is imported into the *HistCite*™ software. However, He et al. (2013), Choi and Luo (2021), and Ehlers et al. (2021) were not found, so these three papers are not included.

[12]Although the paper by Matsumura et al. (2014) is classified into the carbon disclosure group according to its focus, it also investigates the carbon risk issue.

[13]More information about the TCFD can be found at https://www.fsb-tcfd.org/.

TABLE 4 Historical co-citations of reviewed papers (in chronological order).

No.	Author(s) and year	Journal	LCS
1	Busch and Hoffmann (2011)	*Business and Society*	14
2	Iwata and Okada (2011)	*Ecological Economics*	8
3	Aggarwal and Dow (2012)	*The European Journal of Finance*	5
4	Gallego-Álvarez (2012)	*Business Strategy and the Environment*	7
5	Nishitani and Kokubu (2012)	*Business Strategy and the Environment*	7
6	Hatakeda et al. (2012)	*Environmental and Resource Economics*	6
7	Chapple et al. (2013)	*Abacus*	22
8	Fujii et al. (2013)	*Business Strategy and the Environment*	9
9	Griffin and Sun (2013)	*Journal of Accounting and Public Policy*	5
10	Chakrabarty and Wang (2013)	*Thunderbird International Business Review*	2
11	Luo and Tang (2014)	*Pacific Accounting Review*	5
12	Li et al. (2014)	*Review of Accounting and Finance*	6
13	Saka and Oshika (2014)	*Sustainability Accounting, Management and Policy Journal*	5
14	Matsumura et al. (2014)	*The Accounting Review*	28
15	Wang et al. (2014)	*Business Strategy and the Environment*	4
16	Misani and Pogutz (2015)	*Ecological Economics*	6
17	Lannelongue et al. (2015)	*Business Strategy and the Environment*	2
18	Kim et al. (2015)	*Journal of Cleaner Production*	9
19	Clarkson et al. (2015)	*European Accounting Review*	21
20	Lee et al. (2015)	*International Journal of Production Economics*	3
21	Oestreich and Tsiakas (2015)	*Journal of Banking and Finance*	3
22	Delmas et al. (2015)	*Organization and Environment*	7
23	Trumpp and Guenther (2017)	*Business Strategy and the Environment*	8
24	Liesen et al. (2017)	*Journal of Business Finance and Accounting*	3
25	Griffin et al. (2017)	*Contemporary Accounting Research*	17
26	Baboukardos (2017)	*Accounting Forum*	3
27	Lewandowski (2017)	*Business Strategy and the Environment*	3
28	Broadstock et al. (2018)	*British Accounting Review*	6
29	Nguyen (2018)	*Australian Journal of Management*	4
30	Cooper et al. (2018)	*Journal of Accounting and Public Policy*	3
31	Jung et al. (2018)	*Journal of Business Ethics*	14
32	Balachandran and Nguyen (2018)	*Journal of Banking and Finance*	3
33	Zhou, Zhang, et al. (2018)	*Business Strategy and the Environment*	3
34	Lemma et al. (2019)	*Business Strategy and the Environment*	4
35	Herbohn et al. (2019)	*Journal of Business Ethics*	1
36	Schiemann and Sakhel (2019)	*European Accounting Review*	2
37	Albarrak et al. (2019)	*Business Strategy and the Environment*	6
38	Alsaifi et al. (2020a)	*Business Strategy and the Environment*	2
39	Bui et al. (2020)	*Accounting and Finance*	4
40	Ilhan et al. (2021)	*Review of Financial Studies*	3
41	Bolton and Kacperczyk (2021)	*Journal of Financial Economics*	1

3 | MEASURES OF CARBON RISK AND CARBON DISCLOSURE

3.1 | Carbon risk measures

Researchers have contributed to the investigation of the impact of climate change-related carbon risk, demonstrated in several review studies from different perspectives. For example, Velte et al. (2020) convey an understanding of the financial consequences and governance-related determinants. Borghei (2021) presents the recent growth in the carbon disclosure literature and addresses its fragmentation, and He et al. (2021) describe the development of knowledge in research on carbon accounting.

In this review, we broadly treat climate change-related emission issues as carbon risk (e.g., GHG emissions, carbon emissions). The extant literature defines the measure of carbon risk differently. We generally summarise carbon risk measures using four proxies. The first proxy is the absolute carbon emissions, expressed as the emitted GHG amount (e.g., tonnes of CO_2-e).[14] A higher number of carbon emissions indicates a higher carbon risk. This proxy is the most direct measure of carbon risk, representing emitting nature of resource-intensive industries. It may capture various types of transition risk, such as market risk reflected in investment reduction in firms with high emissions, policy risk due to carbon-related new policies in place, and technology risk because of the requirement of technological innovation in reducing carbon emissions. This proxy for carbon risk has been used widely in previous studies. For example, Bolton and Kacperczyk (2021) use the carbon emission amount to represent carbon risk. However, Chakrabarty and Wang (2013) use the difference between the predicted and actual carbon emissions. Similarly, Gallego-Álvarez et al. (2015) use carbon emission reduction. Other studies using this carbon risk proxy include Luo and Tang (2014), Matsumura et al. (2014), Wang et al. (2014), Misani and Pogutz (2015), Griffin et al. (2017), Lewandowski (2017), Jung et al. (2018), Busch et al. (2020) and Basse Mama and Mandaroux (2021).

The second proxy is the carbon intensity (or emission intensity), which is normally expressed as a ratio of carbon emissions[15] to a particular item on the balance sheet (e.g., total assets) or income statement (e.g., total sales). Some studies utilise the industry-adjusted carbon intensity, measured by the difference between the carbon intensity of a firm and the corresponding industry's carbon intensity median (e.g., Brouwers et al., 2018). The carbon intensity accounts for the firm size or specific activity in estimating carbon emissions, reflecting the average of emissions per unit of output which captures a firm's pollution propensity (Hoffmann & Busch, 2008). For example, the amount of emissions divided by the equity market value is used to measure the average emissions per unit value added (e.g., Ilhan et al., 2021; Patten, 2002). Similarly, a ratio of carbon emissions to sales revenue reflects the emission amount required to produce the product or service. A firm with higher carbon intensity may suffer relevant market risk because of demand reductions in its product or service and investment. The carbon intensity proxy is also frequently used in the literature, see, for example, Busch and Hoffmann (2011), Aggarwal and Dow (2012), Gallego-Álvarez et al. (2014), Saka and Oshika (2014), Li et al. (2014), Trumpp and Guenther (2017), Bui et al. (2020) and Kabir et al. (2021).[16]

The third proxy is based predominantly on climate change-related events, which are considered exogenous shocks in carbon risk. Using the Kyoto Protocol ratification as a shock faced by

[14]In our review, the absolute carbon emission proxy also includes the difference between predicted and actual carbon emissions (e.g., Chakrabarty & Wang, 2013) and the change in carbon emissions (e.g., Gallego-Álvarez et al., 2015). Other emission expressions are also included in this category. For example, Trinks et al. (2020) use a ratio of projected to actual carbon emissions and Wang et al. (2021) combine inputs, desirable outputs (economic outputs) and undesirable outputs (carbon emissions) to represent carbon efficiency.

[15]In most studies, the carbon emission is measured using the weight unit (e.g., tonne), whereas it may also be measured using the dollar unit (i.e., yen) (e.g., Hatakeda et al., 2012).

[16]In contrast to the common form of carbon intensity, Nishitani and Kokubu (2012) and Brouwers et al. (2018), and Liesen et al. (2017) use its inverse form, e.g., sales divided by the volume of carbon emissions.

Australian firms with higher carbon emissions, Nguyen (2018) investigates the impact of carbon risk on firm performance, while Nguyen and Phan (2020) explore the effect of carbon risk on the cost of capital.[17] In these two studies, carbon risk is defined as the uncertainty in future carbon performance and is unobservable. To proxy for a firm's carbon risk, Herbohn et al. (2019) focus on the reporting of a firm around bank loan announcements. Neudorfer (2021) studies the heterogeneous tail risk response of fossil-fuel companies around the unburnable carbon news, which is claimed as the first climate science news regarding the stranded fossil fuel industry (Meinshausen et al., 2009).[18] Related to the more ambitious climate target announcement (the Paris Agreement), Monasterolo and De Angelis (2020) analyse whether stock markets price this climate announcement by investigating the change in the systematic risk based on low-carbon and carbon-intensive indices. The event-related proxy for carbon risk is more likely to indicate relevant policy risk faced by a firm, as each announced event conveys information that a firm with high carbon exposure may be heavily impacted by regulatory compliance.

The fourth proxy is associated with a carbon emission score or carbon performance rating, determined by how firms participate in projects related to carbon information disclosure or how firms are penalised if violating relevant carbon emission regulations. Based on firms' commitment and effectiveness in reducing carbon emissions, Qian et al. (2020) use a carbon emission score to proxy for caron performance, with a higher score indicating a higher level of carbon performance (i.e., lower carbon risk). They examine the market response to Australian carbon policy changes and show that the market prefers improved carbon performance rather than policy uncertainties. Zhou, Zhang, et al. (2018) employ an ordinal variable, determined by the punishment for carbon pollution violation. Their work demonstrates that the carbon risk proxy captures the market risk shown in debt financing. Moreover, Ganda (2018) considers a carbon performance rating according to the specifications of the CDP in South Africa. The proxy for carbon risk is associated with the emission-related focus on firms' climate change awareness and climate change mitigation and adaptation. As such, this carbon risk proxy captures the transition risk from compliance with climate-related policies and regulations, as well as physical risks exposed in the process of mitigating and adapting to extreme weather events (e.g., drought, flood) that probably arise from high carbon emissions and global warming.

3.2 | Carbon disclosure measures

The practice of carbon disclosure may improve firms' carbon management and further facilitate firms to well combat not only physical risks but also transition risks. For example, carbon disclosure can improve stakeholders' impression of a firm's carbon performance, increase transparency and improve the firm's reputation in the market. However, carbon disclosure can be either mandatory or voluntary (Borghei, 2021; Hahn et al., 2015). In most countries, it is voluntary and no specific standards exist for interpreting a range of climate-related activities and information (Borghei, 2021; Kolk et al., 2008). The reported information may be inconsistent and cover various scopes. As a result, voluntary carbon disclosure reflects a firm's self-selection in what is reported, which limits investors' ability to assess the firm's performance in tackling climate change.

In Borghei (2021), several relevant carbon disclosure research fields are reviewed, such as determinants, assurance, quality and consequences. Our research focuses on carbon disclosure's financial effects and provides a more comprehensive analysis of this than in Borghei (2021). With the predominantly voluntary nature of carbon disclosure, the measures (proxies) vary. Similar

[17]This method is also used in an unpublished study by Nguyen et al. (2020).

[18]Meinshausen et al. (2009) conduct a comprehensively probabilistic study and make a quantifying GHG emission target to limit global warming to 2°C by 2050. Its published date is used as the news day in Neudorfer (2021).

to Borghei (2021), we find that there is no standard on how to measure carbon disclosure. The prevailing proxy is a dummy variable (or binary variable) used to show whether the firm participates in the CDP or whether the firm discloses carbon emission-related information; if yes, the dummy variable is normally set to a value of 1 and 0, otherwise (Downar et al., 2021; Jiang et al., 2021; Kim & Lyon, 2011; Schiemann & Sakhel, 2019).

Another commonly used proxy is the carbon disclosure score (He et al., 2013; Lemma et al., 2019). For example, using the index of carbon disclosure score from the CDP, He et al. (2013) claim that this index comprehensively covers various carbon-related information, e.g., carbon strategy, governance mechanisms, processes and actions (Luo et al., 2012). Other proxies for carbon disclosure could also be used, such as the number of carbon-related tweets (Albarrak et al., 2019).

4 | FINANCIAL EFFECTS OF CARBON RISK AND CARBON DISCLOSURE

Based on whether each paper is focused on carbon risk or carbon disclosure, we categorise the literature into two groups. The first group includes the financial effects of carbon risk and the second contains the financial effects of carbon disclosure. Several studies examine the financial consequences of both carbon risk and carbon disclosure. For example, Broadstock et al. (2018) examine voluntary disclosure and GHG emissions with business performance. They aim to explore in what ways the voluntary disclosure of emissions affects the relationship between carbon emissions and financial performance. In this instance, voluntary disclosure is considered mainly as a moderator of the emission–financial performance relation. As such, we classify this study to the carbon risk group. Similarly, Luo and Tang (2014) and Bui et al. (2020) are also categorised as part of the carbon risk group.

In contrast, He et al. (2013) investigate the effect of both carbon disclosure and carbon performance on the cost of capital. Their study focuses on how carbon performance affects the relationship between a firm's cost of capital and carbon disclosure. As with He et al. (2013), we identify that Matsumura et al. (2014) and Saka and Oshika (2014) similarly focus on the effect of carbon disclosure. Therefore, these three studies are categorised into the carbon disclosure group.

Following the categorisation by groups shown in Table 3, Tables A1–A5 in the Appendix present our reviews of the grouped papers. In each table, the list of papers is sorted first chronologically (by the year of publication) and then alphabetically (by the last name of the first author). Column (1) shows the author(s) and year published of the reviewed papers. Column (2) indicates the sample features including the country (single or international), sample period and sample size (the number of firms and/or the number of firm-year observations). Column (3) demonstrates the main theory (or underlying mechanism) that guides the research design and/or the hypothesis development for each paper. Our review does not seek to explain these theories but instead only attempts to show relevant theories applied in the reviewed studies, noting that different theories may have proposed different financial effects of carbon risk (e.g., Tzouvanas et al., 2020). Columns (4) and (5) show the main dependent variable(s) and independent variable(s), respectively, if a regression model is applied. The dependent variable may represent firm performance, firm value, the cost of capital (cost of debt or cost of equity) or risk measures of the firm; the independent variable is related to carbon risk (proxied by the level of carbon emissions, carbon intensity or event dummy) or carbon disclosure (dummy, score). Otherwise, the main approaches noted from our review (e.g., event study, portfolio analysis) are presented in column (4). Column (6) presents the main findings of each paper concerning the financial consequences of carbon risk or carbon disclosure.

4.1 | Financial effects of carbon risk

There has been debate on how carbon risk influences aspects of a firm's financial performance, but the literature has been unable to reach a conclusive result. Some studies document that carbon risk has significant financial effects (e.g., Bolton & Kacperczyk, 2021; Chapple et al., 2013; Hatakeda et al., 2012; Kim et al., 2015); however, other studies do not note relevant links (e.g., Gallego-Álvarez et al., 2014, 2015; Li et al., 2014). Our review focuses predominantly on four aspects of financial effects, including financial performance, valuation relevance, the cost of capital and risk profiles (measures).

4.1.1 | Financial performance

The financial performance of a firm is generally measured by return on assets (ROA), return on equity (ROE) and Tobin's Q (Gallego-Álvarez et al., 2014).[19] In most studies, ROA and ROE are considered accounting-based measures, reflecting the short-term perspective of financial performance for a firm, but Tobin's Q as the market-based measure represents financial performance in the long term (Peloza, 2009). Table A1 presents the reviewed studies of carbon risk and financial performance.

Our review shows that most studies document that carbon risk (carbon emissions, carbon intensity) negatively impacts firm performance, an observation shared by Busch and Lewandowski (2018). For the accounting-based financial performance, this negative effect of carbon risk could also be found in the work of Hatakeda et al. (2012) and Gallego-Álvarez et al. (2015). Tzouvanas et al. (2020) show that environmental performance (EP) positively impacts ROA (ROE), in which EP is measured through negative GHG intensity. Their results, therefore, are consistent with the above negative relationship argument. Busch and Hoffmann (2011), Aggarwal and Dow (2012), Delmas et al. (2015) and Brouwers et al. (2018) all document a negative influence of carbon risk on the market-based measure. Moreover, Iwata and Okada (2011), Lee et al. (2015) and Nguyen (2018) show that carbon risk negatively affects both accounting- and market-based performance measures. Wang et al. (2021) present that carbon efficiency positively influences the firm's total asset turnover (TAT) and Tobin's Q. However, their results are in line with the negative effect of carbon risk on financial performance as carbon efficiency is an inverse measure of carbon risk. Wang et al. (2021) further show that the effect of carbon efficiency on TAT and Tobin's Q becomes weaker with improved resource efficiency, suggesting that resource efficiency interacts with carbon efficiency. Furthermore, Wang et al. (2021) show that carbon efficiency does not significantly affect a firm's solvency (current ratio) and profitability (ROA). This may suggest that the short-term returns are offset by the high cost incurred during low-carbon transformation, especially for larger industrial firms.

In contrast, Wang et al. (2014) and Busch et al. (2020) present a positive association between carbon risk and financial performance. Delmas et al. (2015) also show that carbon emissions positively impact ROA, while they document a negative effect on Tobin's Q. As different countries are held to different carbon regulations, it could be argued that the results may vary. When focusing on the Australian environment, Wang et al. (2014) document that the increase in

[19]ROA, ROE and Tobin's Q are commonly used to measure financial performance. Other financial performance measures used in the cited literature include return on investment (ROI), return on invested capital (ROIC), return on sales (ROS), total or net sales, profit and so on. Moreover, researchers may use some of these measures in different ways. For example, Gallego-Álvarez et al. (2015) use ROA to measure *operational* performance, rather than *financial* performance. Tobin's Q is normally expressed as a ratio of an asset's market value to its replacement value. In the literature, the definition of Tobin's Q may be slightly different. See, for example, Aggarwal and Dow (2012) and Delmas et al. (2015).

carbon emissions improves financial performance (Tobin's Q), in contrast to findings for the Japanese market (Iwata & Okada, 2011), international markets (Busch & Hoffmann, 2011) and the US market (Delmas et al., 2015). The positive relationship shown by Wang et al. (2014) is arguably due to Australia's unique economic structure and development environment, where the dominant industries are related to mining. Similarly, Ganda (2018) examines the South African market and shows that carbon performance rating (higher rating, lower carbon risk) is negatively related to ROI and market value added (MVA), but is positively associated with ROE and ROS.

Furthermore, some studies continue to show that the significance of carbon risk's effect on firms' performance varies with time or financial measures. For instance, Gallego-Álvarez et al. (2015) and Lannelongue et al. (2015) show that carbon emission-related measures do not significantly impact ROA. Gallego-Álvarez (2012) documents that the impact of carbon emission reduction on ROA is significant over the period 2006–2007 but is not seen for 2008–2010. Moreover, Brouwers et al. (2018) find insignificant effects on both ROA and ROE, whereas Chakrabarty and Wang (2013) and Trinks et al. (2020) show an insignificant association between carbon emissions-related risk and Tobin's Q.

In several instances, papers examined indicate a non-linear (e.g., U-shaped, inverted U-shaped) impact of carbon risk on the accounting-based measures (Fujii et al., 2013; Lewandowski, 2017; Trumpp & Guenther, 2017), on the market-based measures (Misani & Pogutz, 2015) or on both (Broadstock et al., 2018). For instance, Broadstock et al. (2018) explore how carbon emissions impact a broad range of business performance measures, including sales, profits, net income, assets, ROE and Tobin's Q. An inverted U-shaped effect is noted, showing that for money metric-based performance measures (e.g., profits, assets) this effect is strong, while for ratio-based performance measures (e.g., ROE) it is not as strong. This demonstrates that the measures of financial performance may influence the significance of results (Busch & Lewandowski, 2018).

In other papers reviewed, researchers explore how carbon risk affects corporate policies, such as dividend policy (Balachandran & Nguyen, 2018) and capital structure (Nguyen & Phan, 2020).[20] Balachandran and Nguyen (2018) show that since Australia ratified the Kyoto Protocol, the probability of dividend payments becomes low for higher carbon emitters, and the dividend payout ratio is also low. They argue that the lower dividend payouts are a result of the increase in earnings uncertainty upon ratification. Nguyen and Phan (2020) investigate the impact of carbon risk on the capital structure through a quasi-natural experiment. Their results illustrate that following the Kyoto Protocol ratification, carbon-intensive firms decrease financial leverage, and for those with higher financial constraints, this decrease is more pronounced.

Summarising the findings of the above-reviewed papers, we show that the impact of carbon risk on the firm's financial performance is inconclusive. Some researchers use win–win and win–lose reasonings to explain the relations (Boiral et al., 2012; Stubbs & Cocklin, 2008). Win–win reasoning suggests that efforts to reduce carbon emissions can improve a firm's competitive advantages, while win–lose reasoning argues that efforts in reducing emissions may increase costs that damage the firm's competitiveness. Different carbon risk measures and financial performance measures may also provide an explanation for these inconclusive results (Busch & Lewandowski, 2018; Horváthová, 2010). For example, Busch and Lewandowski (2018) claim that relative emission measures probably generate a significant result than absolute emission measures. Similarly, Busch and Hoffmann (2011) and Delmas et al. (2015) show that the association between carbon emissions and Tobin's Q is negative whereas it becomes positive when using ROA and/or ROE.

[20]These two studies are categorised into the financial performance group as a firm's dividend policy and capital structure policy could provide signals or influence the firm's financial performance. These papers could equally have been presented in other groups (e.g., the valuation relevance group), dependent on the perceptions of different reviewers.

4.1.2 | Valuation relevance

With investors integrating carbon emission information into their investment decision-making, the capital markets have been one of the important drivers in exploring the impact of emission-related issues. As a result, the literature has also explored how carbon risk affects firm valuation. Firm value is generally measured by the market value of equity, computed as the product of the number of shares outstanding and stock price, or derived from relevant valuation models (e.g., Ohlson, 1995). Some investigations focus on event studies, where stock returns, especially abnormal returns (ARs) and/or cumulative abnormal returns (CARs), are used in examining the valuation relevance of carbon risk. Table A2 presents the reviewed papers grouped by the carbon risk's effect on valuation relevance.

Chapple et al. (2013), Baboukardos (2017), Griffin et al. (2017), Cooper et al. (2018), Choi and Luo (2021) and Choi et al. (2021) all document that carbon-related emissions generate a negative effect on a firm's market value. Cooper et al. (2018) further show that a more significant decrease in firm value is found in firms with a higher corporate social responsibility (CSR) score, indicating that higher GHG emitters suffer more penalties when they have a higher reputation for CSR. Consistently, based on the Australian and international settings, Choi et al. (2021) and Choi and Luo (2021), respectively, document that the negative relation is stronger for countries having a carbon pricing scheme and more stringent regulations on environment. All of these results provide empirical evidence that carbon-related risk has an adverse effect on firm valuation.

Clarkson et al. (2015) show that carbon allowance does not affect firm value, whereas carbon allocation shortfalls generate a negative impact. This negative effect is lessened for firms with greater environmental performance. Conversely, Basse Mama and Mandaroux (2021) find an inverted U-shaped association between carbon emissions and market valuation. This concave relationship exists for small firms with low institutional ownership and low analyst coverage.

Other studies in our review explore the carbon risk's effect on stock returns and/or CARs (e.g., Bose, Minnick & Shams, 2021; Herbohn et al., 2019; Luo & Tang, 2014; Oestreich & Tsiakas, 2015; Ramelli et al., 2021; Wen et al., 2020). Luo and Tang (2014) show that direct carbon exposure is negatively related to CARs; however, indirect carbon exposure is not. They further find that carbon disclosure could not reduce the negative effect on CARs, suggesting that carbon disclosure may only increase carbon transparency, rather than the contents of firms' carbon strategies. Qian et al. (2020) explore the market response to three policy change events (i.e., carbon tax, Emission Trading Scheme (ETS), repeal of carbon tax) in Australia. They find that higher market returns could be generated from greater carbon performance during the carbon tax repeal. They further illustrate that public attention is important for firms' carbon performance improvement. In using the first global climate strike as a turning point in climate activism, Ramelli et al. (2021) show that both the industry- and firm-level carbon intensities generate significantly negative impacts on the stock performance during the climate strike. These findings indicate that the adverse effect of carbon intensity could be caused by the greater public focus and knowledge of climate-related issues.

However, Oestreich and Tsiakas (2015) document carbon premia from stock markets, arguing that the markets realise that carbon emitters would receive a free carbon allowance. Herbohn et al. (2019) also show a significantly positive excess loan announcement return when firms with high carbon risk renew their loans, indicating that investors believe bank lenders have taken borrowers' carbon risk exposure into account in making lending decisions. Furthermore, Wen et al. (2020) and Bolton and Kacperczyk (2021) present that carbon emissions positively impact stock returns. This suggests that investors demand compensation for their carbon exposure, whereas Wen et al. (2020) also show that the carbon trading market does not significantly influence abnormal returns for firms participating in carbon emission allowance trading.

Bose, Minnick, et al. (2021) examine how carbon risk impacts corporate acquisitions. They demonstrate that a high carbon-emitting firm probably acquires foreign targets in countries with a worse economic situation, weaker environmental standards or fewer regulations. The CARs around the cross-board acquisition announcements are higher. These findings indicate that acquirers could move their carbon risk offshore to countries with less stringent sanctions, thereby reducing carbon emission-related financial risk. Having achieved this, however, investors would penalise those acquirers that promote corporate social responsibility but have a high level of carbon emissions. This ultimately results in worse abnormal returns.

Overall, researchers document mixed findings regarding the effect of carbon risk on firm valuation. Several studies show a carbon premium of stock returns – a positive association between carbon risk and stock returns (Oestreich & Tsiakas, 2015; Wen et al., 2020). This reflects that investors are aware of the adverse impact of carbon emissions and therefore demand compensation for their carbon exposure. However, most studies demonstrate a negative relationship between carbon risk and firm value, indicating that the market penalises firms for their high emissions and liabilities (Chapple et al., 2013). The penalty is more prominent for firms with higher corporate social responsibility or in countries implementing stringent environmental regulations (Choi et al., 2021; Choi & Luo, 2021; Cooper et al., 2018). In short, if a firm does not take action to mitigate the emission impact, investors will lose confidence in it, leading to damage to its reputation and value. Again, these inconclusive findings may be generated by using different carbon risk and valuation measures, research designs and/or model specifications (Busch & Lewandowski, 2018). Therefore, caution is required in the explanation of these empirical results.

4.1.3 | The cost of capital

The cost of capital represents the cost of a firm in raising funds from both the debt and equity markets. It is generally composed of two components: the cost of debt and the cost of equity. The combination of these two components generates the weighted average cost of capital (WACC). As it reflects investors' estimates of the discount rate for the firm's future cash flows, the cost of capital is an essential factor in firm valuation. While numerous studies have explored the influence of carbon risk on financial performance and firm value, studies examining the impact of carbon risk on the cost of capital are relatively new, with focus only arising over the past 2 years.

Kim et al. (2015), Bui et al. (2020) and Gerged et al. (2021) document the effect of carbon risk on the cost of equity. When examining the cost of debt, more studies are found, including Jung et al. (2018), Zhou, Zhang, et al. (2018), Caragnano et al. (2020), Palea and Drogo (2020), Ehlers et al. (2021), Kleimeier and Viehs (2021), and Morrone et al. (2021). However, Li et al. (2014) explore the carbon risk's effect on both the cost of debt and the cost of equity. Table A3 presents relevant studies.

Both Kim et al. (2015) and Bui et al. (2020) show a positive effect of carbon risk on the cost of equity. In their studies, Easton's (2004) model and Ohlson and Juettner-Nauroth's (2005) model are used to measure the firm's implied cost of equity. Their difference is that Kim et al. (2015) focus on a single country setting (Korea), but Bui et al. (2020) examine a global sample. Moreover, Kim et al. (2015) examine only the impact of carbon risk on the cost of equity, whereas Bui et al. (2020) explore the joint effect of carbon risk and carbon disclosures. Bui et al. (2020) show that the positive association between carbon risk and the cost of equity is mitigated by carbon disclosure. This mitigation is in line with the results of Albarrak et al. (2019) showing a negative impact of disclosure on the firm's cost of equity. As carbon disclosure provides more information for investors to evaluate the firm's performance, it reduces information asymmetry and therefore reduces the required rate on the investments.

While Li et al. (2014) and Gerged et al. (2021) also apply Easton's (2004) model in estimating the cost of equity, they demonstrate different results from Kim et al. (2015) and Bui et al. (2020).

Li et al. (2014) show that carbon intensity does not affect the cost of equity. Gerged et al. (2021), however, document a U-shaped effect of emissions on the cost of equity. This indicates that carbon emissions could decrease the cost of equity up to a certain point, after which any increase in emissions may push up the cost of equity.

When calculating the cost of debt, in general, interest expenses or loan spreads are used. Li et al. (2014), Caragnano et al. (2020), Palea and Drogo (2020) and Morrone et al. (2021) all demonstrate that the cost of debt is positively related to carbon risk, expressed as carbon emissions or carbon intensity. Palea and Drogo (2020) further show that public policies that can drive lenders' fund allocation decisions and climate-related disclosure could mitigate the cost of capital. Jung et al. (2018) find a positive relationship between the cost of debt and carbon risk for firms that fail to participate in the CDP survey. Using a firm's willingness to participate in the CDP survey as a proxy for carbon risk awareness, Jung et al. (2018) further show that the carbon risk penalty is mitigated or even reversed for firms with greater carbon risk awareness, while Zhou, Zhang, et al. (2018) present a non-linear effect of carbon risk on the cost of debt, and also show that this effect is more pronounced for private firms but not for state-owned firms. They further demonstrate that positive public attention could mitigate this relationship, indicative of the significant influence of carbon transparency on the cost of debt.

Ehlers et al. (2021) and Kleimeier and Viehs (2021) use loan spreads to represent the cost of debt in an international setting, whereas they document different results. Kleimeier and Viehs (2021) find a positive association between a firm's loan spreads and its borrowers' carbon emissions, arguing further that this positive relationship is driven by environmental risk rather than by investors' preferences. However, Ehlers et al. (2021) document that carbon intensity has no significant impact on the syndicated loan's margin, proposing instead that the loan margin could be driven mainly by the loan characteristics (e.g., credit rating, term spread) rather than carbon risk.

In summary, regarding the effects of carbon risk on the cost of capital, the general findings are carbon risk increases the cost of capital (cost of debt and cost of equity). This indicates that a firm with a high level of carbon risk is penalised when financing its capital. However, subject to proxies for carbon risk and measures of the cost of capital, inconsistent relationships are observed. Besides, the differences in the sample size, sample period and country setting may also lead to inconclusive results. It is suggested that researchers should be vigilant in explaining and comparing empirical results.

4.1.4 | Risk profiles (measures)

As risk is inherent in any business, a good understanding of risk and risk management is essential for running a successful business. In our review, we find that studies regarding carbon-related effects on firms' risk profiles are limited to the last 2 years, indicating this is a relatively new area of research. To date, there have been only seven published papers in this area (Capasso et al., 2020; Ilhan et al., 2021; Kabir et al., 2021; Monasterolo & De Angelis, 2020; Neudorfer, 2021; Safiullah et al., 2021; Tzouvanas & Mamatzakis, 2021). Table A4 provides a summary of these papers.

Capasso et al. (2020) and Kabir et al. (2021) explore the effect of carbon risk on the firm's default risk (distance-to-default)[21] with both studies documenting a significantly negative relation. While the paper of Capasso et al. (2020) focuses on a single country (US), Kabir et al. (2021) provide empirical evidence for global firms. Moreover, Kabir et al. (2021) consider both direct and indirect carbon emissions whereas Capasso et al. (2020) focus on direct emissions that incorporate only a portion of the transition risk of firms. Kabir et al. (2021) demonstrate that the

[21] In the application, distance-to-default is a reverse measure of default risk.

impact of carbon emissions on default risk can be mitigated through a firm's environmental commitments and activities. They further argue that carbon emissions impact a firm's default risk through ROA and cash flow volatility. Similarly, Safiullah et al. (2021) also show that firms with higher carbon exposure could face a higher cash flow uncertainty, leading to a lower credit rating.

Monasterolo and De Angelis (2020) analyse the systematic risk of low-carbon and carbon-intensive firms in the stock markets (EU, US and global) around the Paris Agreement announcement. They show that stock markets have priced the Paris Agreement by rewarding low-carbon indices (assets) after the announcement, but carbon-intensive indices (assets) have not been penalised at this point. Tzouvanas and Mamatzakis (2021) examine not only the systematic risk, but also the total risk and idiosyncratic risk, showing that carbon risk positively impacts idiosyncratic risk, but negatively affects systematic risk. These results indicate that a lower total risk could be achieved with higher environmental performance (i.e., lower carbon risk), which particularly benefits from the lower idiosyncratic risk.

Both Ilhan et al. (2021) and Neudorfer (2021) explore the impact of carbon risk on the firm's tail risk using option measures. Ilhan et al. (2021) investigate the climate policy uncertainty of S&P 500 firms in the options market. Using the industry carbon intensity as the carbon risk measure, they show a significant effect on implied volatility slope (SlopD) and variance risk premium (VRP) at the firm level, but show no effect on the model-free implied skewness (MFIS); however, while the effect on SlopD remains, it becomes weaker for MFIS and VRP at the sector level. They provide empirical evidence that for high-carbon firms, the cost of using options against downside tail risk is larger. These findings also provide implications for regulation authorities to take action against the potentially severe consequences of climate change.

Neudorfer (2021) designs a quasi-experiment investigating how carbon news impacts tail risk of fossil fuel industry returns. Meinshausen et al. (2009), claimed to be the first climate science news article relating to the stranded fossil fuel industry, was published on 30 April 2009. The release date of this pivotal study is designated the 'event date' for later studies such as Neudorfer (2021). Neudorfer (2021) estimates tail risk using two option-implied measures: the first being the option-implied conditional value at risk (CVaR) based on industry returns, extracted from put options of the exchange-traded fund; the second being the implied 5% value at risk ($VaR_{5\%}$) based on the firm level's call options. The findings show that regardless of size, both small and large firms are equally impacted by carbon risk. This indicates that large firms may not have necessarily been in a better position to hedge the carbon risk. Not surprisingly, firms that hold a higher level of fossil fuel reserves are subject to higher tail risk.

Following these studies, we suggest that there will be increased future research investigating how carbon-related risk affects a firm's risk profiles, such as supply chain risk, crash risk and operational risk. Linking the relationship between these types of risk and carbon risk to corporate governance and investment determinants may become a potential future research direction.

4.2 | Financial effects of carbon disclosure

Carbon emissions normally generate negative financial effects (see Section 4.1), whereas firms still choose to disclose their carbon-related information. The reason is that disclosure can reduce information asymmetry between internal management and external investors. As such, the resources are efficiently allocated (Healy & Palepu, 2001), which may improve the operation and performance of the firm. However, extant studies document different financial effects of carbon disclosure. Table A5 summarises these studies.

By combining 10 accounting- and market-based financial measures to construct an index, Alsaifi et al. (2020a) document a positive association between carbon disclosure and the index. Siddique et al. (2021) also show that carbon disclosure positively impacts firms' Tobin's Q,

but negatively impacts ROA. These findings indicate that although the costs of carbon disclosure might outweigh the benefits in the short term, firms will benefit from high-quality carbon disclosure in the long term. Downar et al. (2021) explore how carbon disclosure mandates affect financial operating performance, as opposed to voluntary carbon disclosure. They show that mandatory carbon disclosures do not affect firms' gross margins, suggesting that firms' carbon disclosure does not significantly increase the cost of sales. They find no empirical evidence that suggests that carbon disclosure mandates exacerbate firms' operating performance.

Matsumura et al. (2014) and Saka and Oshika (2014) investigate the influence of carbon disclosure on firm value and show that carbon disclosure generates a positive effect on equity value. At the same time, they show that carbon risk (carbon emissions or carbon intensity) negatively impacts firm valuation. Matsumura et al. (2014) further show that all carbon emitters are penalised by financial markets. Firms will suffer a higher penalty if not disclosing carbon-related information.

Based on the event study, Griffin and Sun (2013) show that voluntary carbon disclosure generates a positive stock return, and smaller firms' shareholders benefit more than those from larger firms, as they rarely have other channels to access competing information. Liesen et al. (2017) document that stock portfolios constructed by buying stocks from firms reporting carbon emission information and selling stocks from firms not reporting this information earn a positive risk-adjusted return. They further illustrate that financial markets value the quality of carbon disclosure. Jiang et al. (2021) also provide empirical evidence that carbon disclosure positively influences firm value. In contrast, Alsaifi et al. (2020b) report a negative market response to carbon disclosure announcements through the CDP, and this response is more negative and significant for carbon-intensive firms, which are mainly driven by small firms.

Moreover, Kim and Lyon (2011) could not provide evidence to show that the CDP participation would increase shareholder value (focus on CAR) for the overall Financial Times Global 500 companies. However, they show that shareholder value can be improved following the Kyoto Protocol ratification of Russia, indicating that Russia's ratification imposes regulatory pressures on the US and other non-ratifying countries.

Researchers also investigate the association between carbon disclosure and the cost of capital (Albarrak et al., 2019; He et al., 2013; Lemma et al., 2019). While both He et al. (2013) and Albarrak et al. (2019) document that carbon disclosure negatively impacts the cost of equity, Lemma et al. (2019) find that voluntary carbon disclosure does not affect either the cost of debt or the cost of equity. However, Lemma et al. (2019) report a significantly negative impact of carbon disclosure on WACC, suggesting that high-quality disclosure reduces the overall cost of capital. They further show that firms perform better at carbon disclosure if they have higher carbon risk.

Finally, studies also explore the effect of carbon disclosure on agency cost (Zhou, Zhou, et al., 2018), the bid-ask spread (Schiemann & Sakhel, 2019) and stock price volatility (Krishnamurti & Velayutham, 2018). These studies all demonstrate that carbon disclosure presents negative effects. That is, carbon disclosure reduces agency costs, information asymmetry and stock price volatility. Adhikari and Zhou (2021) document consistent results with Schiemann and Sakhel (2019) on the bid-ask spread; however, they show that carbon disclosure increases price volatility, in contrast to Krishnamurti and Velayutham (2018).

In short, most of the above-reviewed studies have documented a positive financial effect of carbon disclosure – improving a firm's financial performance and value and reducing the cost of capital and other relevant risks. However, some conflicting results have been presented. There could be a variety of different reasons for this. First, carbon disclosure itself is defined without standards and can be mandatory or voluntary. As a result, its measure or proxy varies. Next, financial effects are also measured differently. For example, financial performance can be accounting-based or market-based measures, which reflect a firm's operations over different periods (short-term or long-term). Lastly, sample settings (single country or global setting), sample

periods and research designs are all potential factors that cause inconsistent results. Thus, attention is required when commenting on or using these empirical results.

5 | CONCLUSIONS AND FUTURE RESEARCH

We conduct a critical review of the empirical literature concerning the financial effects of carbon risk and carbon disclosure. A total of 78 papers are reviewed, having been published in journals with a rank B and above of the ABDC 2019 for the period from 2011 to 2021. Over recent years, in particular since the Paris Agreement took effect in 2016, with the ambitious target to limit global warming, firms have been under pressure to reduce carbon emissions and have been encouraged to disclose carbon information. As a result, we also see an increase in related research studies, especially in the past 2 years. This review provides a summary of the literature examining the financial effects of carbon risk and carbon disclosure.

We categorise the carbon-related financial consequences into financial performance, valuation relevance, cost of capital and risk measures (e.g., default risk, tail risk). Our review shows that the literature focuses mainly on the financial performance and valuation relevance of carbon risk and carbon disclosure, while some studies have begun to explore how carbon risk and disclosure impact the cost of capital of a firm and risk profiles. In general, studies show that carbon risk damages firm performance and valuation, and increases the cost of capital and other risks, whereas carbon disclosure has a converse effect on these areas.

Up to now, no consensus has been reached regarding the financial consequences of carbon risk and carbon disclosure. This may arise from various factors, such as sample sizes and periods, country coverage, research design and firm characteristics. We also suggest that the variation of results may be caused by different measures of financial consequences, and/or carbon risk and carbon disclosure. For example, financial performance could be assessed by accounting-based measures (e.g., ROA, ROE) and/or market-based measures (e.g., Tobin's Q), which represent short-term and long-term firm performance, respectively. Regarding carbon-related measures, there are no consistent standards to define carbon risk, and carbon disclosure is voluntary in most business contexts. In this review, we identify four proxies for carbon risk: the level of carbon emissions, carbon intensity, carbon event-related measures (e.g., dummy variables) and rating/score based on carbon performance. These carbon risk proxies are not comparable, so findings become inconsistent and sometimes contradictory. Furthermore, due to the nature of voluntary disclosure, there are different methods to measure carbon disclosure. As such, future studies may utilise one or more alternative measures to validate the results.

Studies on the financial effects of carbon risk and carbon disclosure are insufficient. We propose several potential research directions. First, we find that most of our reviewed papers focus on how carbon risk and carbon disclosure impact firms' financial performance and valuation. We suggest that more attention should also be paid to examining the influence on the cost of capital and risk profiles. This is because most risks are critical factors in evaluating the firm value and sustainability. Firms should integrate effective risk management into their operations and strategies.

Second, while more studies relate carbon risk and/or carbon disclosure to the equity and debt markets, derivatives markets may be an avenue for future research as the derivatives markets may contain rich or different information compared with the equity and debt markets. For example, the derivatives market-based measures can reflect investors' forward-looking expectations. This provides useful information for market trading activities as derivative contracts can incorporate investors' beliefs about climate transition risk. The ex-ante expectation of risk is more important than the ex-post realised risk in investment decision-making.

Third, although our review does not focus on the determinants of carbon-related issues, we find that governance aspects are mainly discussed in the extant literature. We suggest that other

determining factors (e.g., carbon awareness of stakeholders or the public, environmental beliefs and risk perceptions) should be explored. The studies can investigate how these determinants influence carbon risk and drive carbon disclosure, and further investigate their mediating roles in the relationship between carbon risk and disclosure and financial consequences. The potential research should provide insights for businesses, policymakers and regulators on how investors' or the public's behaviour influences climate change-related strategies.

Finally, with the increasing threat of climate-related risks, it becomes more important for firms to disclose their carbon emission information, as well as corresponding risk measurements, opportunities, strategies and actions. Through effective disclosure, information asymmetry can be reduced and stakeholders can correctly assess the firm's emission exposure. This is helpful to mitigate both transition risks and physical risks. Currently, while there exist mandatory reporting schemes for carbon emissions in some countries, such as Australia, the European Union, Japan and the United States, voluntary reporting frameworks have been increasingly adopted, including the widely used CDP and recently released TCFD (Herbohn et al., 2022). Our review shows that even if the number of research publications on carbon disclosure has been very stable in the past several years, it is still a single-digit number. Therefore, we call for more empirical studies to address inconsistent issues and investigate how firms use disclosure mechanisms to manage risk and achieve corporate social responsibility and economic sustainability.

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The data used in this study are openly available in a public repository.

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APPENDIX: REVIEWED PAPERS BY GROUPS

TABLE A1 Effects of carbon risk on financial performance.

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Busch and Hoffmann (2011)	• International • 2006 • 174 firms	• Instrumental stakeholder theory • Competitive advantage theory	• ROA, ROE • Tobin's Q	• Carbon intensity • Carbon management (questionnaire: score)	• Carbon performance (negative carbon intensity) has a positive impact on Tobin's Q, but does not affect ROA and ROE • A negative association is documented between carbon management and ROE and Tobin's Q, indicating that any effort made by the management to improve the environment's performance may be a resource waste
Iwata and Okada (2011)	• Japan • 2004–2008 • 268 firms (186 clean firms and 82 dirty firms)	• Stakeholder theory • Market mechanism	• ROA, ROE, ROI, ROIC, ROS • Tobin's Q	• Carbon emission intensity • Waste emission intensity	• Carbon emission reduction improves financial performance (both accounting- and market-based measures) for the sample as a whole or clean industry, but there is no significant impact on the dirty industry • Waste emissions do not significantly impact the financial performance of firms • The market mechanism alone could not solve environmental issues, appropriate regulations from the government are required
Aggarwal and Dow (2012)	• US • 2009 • 230–426 firms	• Cap-and-trade mechanism • Stock market mechanism	Tobin's Q	• Carbon emission intensity • Environmental impact score (EIS)	• A negative relationship exists between carbon intensity and Tobin's Q, indicating that higher exposure to emissions causes a decrease in Tobin's Q • EIS, a cost measure of mitigating emission exposure, is negatively associated with Tobin's Q
Gallego-Álvarez (2012)	• International • 2006–2010 • 89 firms	N/A	ROA, ROE	Variation of carbon emissions	• Carbon emission reduction in the period 2006–2007 has a significantly negative effect only on ROA of 2007, but has no significant impact on ROA over 2008–2010 • Carbon emission reduction in the period 2006–2007 does not show a significant effect on ROE • Firms are more conservative during crisis times and stop investing in sustainable projects

TABLE A1 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Hatakeda et al. (2012)	• Japan • 2006–2007 • 1089 firm-year observations	N/A	ROA	Carbon intensity reduction	• Carbon emission reduction positively impacts a firm's profitability • As an indicator of environmental proactiveness, the ISO 14001 adoption, does not provide sufficient incentives to reduce carbon emissions. Other factors, such as uncertainty, ownership structure and financial flexibility may be important in achieving carbon emission reduction
Nishitani and Kokubu (2012)	• Japan • 2006–2008 • 641 firms (1888 firm-year observations)	Agency theory	Tobin's Q	Carbon emission reduction (inverse of carbon intensity)	• A positive relation is documented between carbon emission reduction and Tobin's Q, indicating that higher emission reduction improves firm value • The implementation of environmental management (ISO 14001) facilitates firms to reduce emissions
Chakrabarty and Wang (2013)	• US • 2001–2009 • 264 firm-year observations	• Signalling theory (sale effectiveness) • Organisational learning theory (product leadership) • Utility maximisation principle (ROE)	• Sales effectiveness • Product leadership (KLD rating) • ROE	Climate change mitigation (difference between predicted and actual carbon emissions)	• A positive relationship exists between climate change mitigation and sales effectiveness (product leadership) • This positive association is stronger for highly internationalised firms • No significant effect is found on ROE
Fujii et al. (2013)	• Japan Sample A (carbon emissions): • 2006–2008 • 758 firm-year observations Sample B (toxic emissions): • 2001–2008 • 2498 firm-year observations	N/A	• ROA, ROS • Capital turnover (CT)	• Carbon emission intensity (sales per CO_2 emission) • Toxic risk (sales per toxic score)	• Carbon emissions generate a significantly negative and linear impact on ROA, and a negative and non-linear impact on ROS, but do not affect CT • Aggregated toxic risk has a significant inverted U-shaped relation with ROA and CT, but a negative and linear relation with ROS

(Continues)

TABLE A1 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Gallego-Álvarez et al. (2014)	• International • 2006–2009 • 855 firms	• Trade-off theory • Stakeholder theory	ROA	Carbon emission intensity	• No significant synergy is found between carbon performance and financial performance in normal times; however, the synergistic effect is higher during the economic crisis. This indicates that firms will benefit by investing in sustainable projects during worse economic periods
Wang et al. (2014)	• Australia • 2006–2008 • 69 firms	Stakeholder theory	Tobin's Q	Carbon emissions	• Carbon emissions positively influence financial performance, in contrast to findings in some previous studies. It is argued that this positive effect arises from Australia's unique economic structure and development (i.e., dominant mining industry)
Delmas et al. (2015)	• US • 2004–2008 • 1095 firms	Process-based view of environmental issues	• ROA • Tobin's Q	Carbon emissions	• Carbon emissions positively affect ROA, but negatively impact Tobin's Q • The impact depends on the time horizon. Decreased carbon emissions harm (benefit) the short-term (long-term) financial performance
Gallego-Álvarez et al. (2015)	• International • 2006–2009 • 89 firms	Resource-based view (RBV) theory	ROA, ROE	Carbon emission reduction	• Carbon emission reduction generates a positive effect on ROE, but has no significant impact on ROA • In general, firms' better environmental behaviour leads to higher financial performance
Lannelongue et al. (2015)	• Spain • 2010–2011 • 204 firms	Environmental management productivity	• ROA, ROE • Profits before taxes	• Effort in environmental management (Questionnaire) • Carbon emission • Environmental management productivity (EMP)	• The implementation of environmental management negatively impacts ROE and profits, but does not affect ROA • Benefits from environmental management (i.e., lower carbon emission) positively impact ROA and profits rather than ROE • EMP exhibits a significantly positive effect on all financial performance measures

TABLE A1 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Lee et al. (2015)	• Japan • 2003–2010 • 362 firms	Theory of information	• ROA • Tobin's Q	• Carbon emission • Environmental R&D investment	• A negative association exists between carbon emissions and ROA (Tobin's Q), indicating carbon emissions decrease firm performance in both the short term and long term • Corporate environment investment is negatively related to firm value • The market's response varies with a firm's positive and negative environmental performance, which is more significant and persistent for negative performance
Misani and Pogutz (2015)	• International • 2007–2013 • 127 firms (766 firm-year observations)	Stakeholder theory	Tobin's Q	Carbon emissions	• Carbon emissions affect Tobin's Q non-linearly (i.e., inverted U-shaped) • Firms with intermediate carbon performance achieve the highest financial performance. This relation is moderated by improved stakeholder management
Lewandowski (2017)	• US • 2003–2015 • 1640 firms (7625 firm-year observations)	• Stakeholder theory • Natural-resource-based theory	• ROA, ROE, ROS, ROIC • Tobin's Q	• Carbon emissions • Change in carbon emissions	• A non-linear association is found between carbon emissions and firm profitability (except ROS) • Change in carbon emissions generates a linear and positive impact on ROS but negatively affects Tobin's Q • The improvement in carbon performance somehow enhances the profitability of firms but may have deteriorated their stock market performance. This may have been a possible reason why some firms were reluctant to reduce their carbon emissions
Trumpp and Guenther (2017)	• International • 2008–2012 • 2361 firm-year observations	• Stakeholder theory • Trade-off theory	• ROA • Stock price	• Carbon emissions intensity • Waste intensity	• A non-linear association exists between carbon intensity (or waste intensity) and ROA • This non-linear association between carbon intensity and stock price only holds for manufacturing industries • The link between environmental and financial performance is also determined by the level of environmental performance. Specifically, a negative (positive) relation exists for firms with low (high) environmental performance

(Continues)

TABLE A1 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Balachandran and Nguyen (2018)	• Australia • 2002–2013 • 16,844 firm-year observations	Life-cycle theory	• Current dividend (dummy) • Current dividend payout ratio	Carbon risk (dummy: whether a firm is a polluter)	• Following Australia ratifying the Kyoto Protocol, the probability of dividend payment is lower for higher carbon emitters, and the dividend payout ratio is also low • The lower dividend payouts are caused by the increase in earnings uncertainty of post ratification
Broadstock et al. (2018)	• UK • 2000–2015 • 688 firm-year observations (with CO_2 data)	Underpinning theory	• Money metrics: Asset Sales Net income Operating profits EBITDA Stock price Market capitalisation • Ratio metrics: ROE Tobin's Q	• GHG emissions • Carbon disclosure	• A non-linear association is documented between carbon emissions and money metric performance measures (e.g., assets, profits), but this relation is not as strong for ratio-based performance measures (ROE, Tobin's Q) • Decisions of reporting carbon emissions are not directly affected by the attitudes on social or governance disclosure, suggesting a disassociation between environmental responsibility and social responsibility
Brouwers et al. (2018)	• International • 2005–2012 • 368 firms (2593 firm-year observations)	• Stakeholder theory • Economic theory-free allocation	• ROA, ROE • Tobin's Q	Carbon emission intensity	• Carbon emissions negatively impact Tobin's Q, but do not affect ROA and ROE in the full sample • Carbon emissions impose significant and negative impacts on all financial performance measures for firms without carbon cost pass-through. The negative impact of emissions on financial performance can be mitigated for firms passing on carbon costs to consumers • A firm's good carbon performance may not always be rewarded
Ganda (2018)	• South Africa • 2014–2015 • 63 firms	• Legitimacy theory • Stakeholder theory • Institutional theory	• ROE, ROI, ROS • Market value added (MVA)	Carbon performance rating	• Carbon performance positively impacts ROE and ROS, but negatively affects ROI and MVA • These effects are moderated by the level of firm growth. A higher growth rate enlarges the positive influence of carbon performance on financial performance

TABLE A1 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Nguyen (2018)	• Australia • 2000–2014 • 21,000+ firm-year observations (main test)	Financial constraint mechanism	• Probability of loss • ROE • Tobin's Q	Carbon risk (polluter: dummy; post-Kyoto Protocol ratification: dummy)	• Following the Kyoto Protocol ratification, polluting firms experience lower financial performance, resulting from large environmental protection-related costs • For firms with financial constraints, carbon risk's negative effect is more pronounced
Busch et al. (2020)	Replication of Delmas et al. (2015): • US • 2005–2014 • 1095 firms Extension of Delmas et al. (2015): • International • 2005–2014 • 4873 firms (27,986 firm-year observations	N/A	• ROA • Tobin's Q	Carbon emissions	Replication tests: • Higher carbon emissions improve ROA, consistent with Delmas et al. (2015) • No evidence is found that higher carbon emissions decrease Tobin's Q, in contrast to Delmas et al. (2015) Extension tests: • Higher carbon emissions improve both ROA and Tobin's Q • In summary, carbon risk positively influences the firm's short-term financial performance; the association between carbon risk and long-term financial performance varies with the research design (e.g., country setting, sample period)
Nguyen and Phan (2020)	• Australia • 2002–2013 • 2092 firms (15,484 firm-year observations)	• Trade-off theory • Pecking order theory	• Book leverage (total debt/ book value of assets) • • Market leverage (total debt/market value of assets)	Carbon risk (polluter: dummy; post-Kyoto Protocol ratification: dummy)	• Following the Kyoto Protocol ratification, carbon risk negatively impacts the financial leverage (both book and market leverage) of carbon-intensive firms • This impact is more pronounced for firms that suffer higher financial constraints
Trinks et al. (2020)	• International • 2009–2017 • 1572 firms	Production theory	• ROA • Tobin's Q	Carbon efficiency (ratio of projected to actual carbon emissions)	• Carbon efficiency is positively associated with ROA, but no significant association exists with Tobin's Q • Carbon-efficient firms perform well in the short term, and are rewarded by the stock market value due to lower systematic risk

(Continues)

TABLE A1 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Tzouvanas et al. (2020)	• International • 2005–2016 • 288 firms	• Agency theory • Instrumental stakeholder theory • Natural resource-based view • Neoclassical theory • Slack resource argument	• ROA, ROE • Industry-adjusted ROA, ROE	• Environmental performance (EP) (measured by negative GHG intensity) • Industry-adjusted EP	• EP positively impacts financial performance (FP: ROA and ROE) • This positive effect is heterogeneous across the conditional distribution of FP • For firms with high profitability, FP and EP are endogenously correlated
Wang et al. (2021)	• China • 2015–2019 • 38 firms	N/A	• Current ratio (CR) • Total asset turnover (TAT) • ROA • Tobin's Q	• Carbon efficiency (SBM-DEA model)	• Carbon efficiency positively impacts both TAT and Tobin's Q • This positive relationship becomes weaker with the resource efficiency improvement, suggesting an interaction between carbon and resource efficiency • Carbon efficiency does not significantly affect a firm's profitability (ROA) and solvency (CR). The reason may have been that the short-term excess returns are offset by the high cost arising from a firm's low-carbon transformation, especially for large industrial firms

Abbreviations: ROA, return on assets; ROE, return on equity; ROI, return on investment; ROIC, return on invested capital; ROS, return on sales.

TABLE A2 Effects of carbon risk on valuation relevance.

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Chapple et al. (2013)	• Australia • 2009–2013 • 58 firm-year observations	N/A	• Market value of equity (Ohlson's, 1995 model) • Share price	Carbon intensity	• Carbon intensity negatively affects firm value • The market may evaluate a market value penalty for firms affected by the proposed Emission Trading Scheme (ETS), decreasing the value from 7% to 10% of the market capitalisation
Luo and Tang (2014)	• Australia • 2011 • 48 firms (336 firm-event observations)	• Voluntary disclosure theory • Market mechanism	• CAR • Standardised CAR (SCAR)	• Carbon emissions (Scope 1 and Scope 2) • Carbon disclosure (score) • Carbon reduction target (dummy)	• Direct carbon exposure (Scope 1 emissions) has a negative association with CAR, but indirect carbon exposure (Scope 2 emissions) has no significant link with CAR, as it is not covered by the carbon tax • Carbon disclosure does not significantly reduce the effect of carbon emissions on CAR, suggesting that carbon disclosure may only increase the transparency of carbon-related information, rather than the substance of firms' carbon strategies • The carbon-incentive system does not effectively improve investors' confidence in a firm dealing with climate change
Clarkson et al. (2015)	• International • 2006–2009 • 843 firm-year observations	• Economic theory • Ohlson's valuation model	• Market value of equity (Ohlson's, 1995 model)	• Carbon allowance • Carbon allocation shortfall	• No association is found between carbon allowances and firm value • Carbon allocation shortfalls negatively affect firm valuation. This negative effect could be mitigated for firms with improved environmental performance
Oestreich and Tsiakas (2015)	• Germany • 2003–2012 • 65 firms	Economic mechanism (carbon risk effect; cash flow effect)	Stock return	Carbon risk (dirty-minus-clean factor)	• Portfolio analyses document a significant carbon premium for November 2003–March 2009 • Regression analyses also present a positive correlation between carbon risk and expected returns for November 2003–March 2009 • Both portfolio and regression results suggest that the carbon premium largely disappears after March 2009 • During November 2003–March 2009, the market might know with certainty that carbon emitters would receive a free carbon allowance

(Continues)

TABLE A2 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Baboukardos (2017)	• UK • 2010–2014 392 firms (1566 firm-year observations)	N/A	Market value of equity	GHG emissions	• GHG emissions negatively affect the firm's market value • The negative relationship is mitigated after the introduction of environmental reporting regulation
Griffin et al. (2017)	• US • 2006–2012 • 3276 firm-year observations	Voluntary disclosure theory	Stock price	Carbon emissions	• Carbon emissions negatively impact the equity value • Carbon emissions affect the equity value via emission information channels (e.g., 8-K filing) rather than the Carbon Disclosure Project (CDP)
Cooper et al. (2018)	• US • 2010–2014 • 392 firms (1566 firm-year observations)	Voluntary disclosure theory	Market value of equity	• GHG emissions • CSR score	• GHG emissions negatively impact a firm's market value • For firms with a higher CSR score, the decrease in the market value due to GHG emissions is greater. This indicates that a higher GHG emitter suffers more penalties when its reputation for CSR is higher
Herbohn et al. (2019)	• Australia • 2009–2015 • 81 firms	• Information asymmetry theory • Modern banking theory	CAR	Carbon risk (dummy)	• A significant and positive excess loan announcement return is documented for high carbon risk firms to renew their loans. This indicates that investors believe bank lenders have considered borrowers' carbon risk exposure when making lending decisions
Qian et al. (2020)	• Australia • 2008–2014 • Various firm numbers around events	Win–win resolution	CAR	Carbon emission score	• Higher market returns are noted as a result of improved carbon performance after the carbon tax was repealed, rather than during either ETS or carbon tax changes • The market responds more to the increasing public demand for improved carbon performance than to regulation uncertainties
Wen et al. (2020)	• China • 2009–2018 177 firms (52 participating firms and 125 nonparticipating firms)	Economic mechanism (cash flow effect; carbon risk effect)	Abnormal return	Carbon risk (dummy)	• The establishment of China's carbon emission trading scheme positively impacts excess returns of firms that participate in the carbon trading programme • A carbon premium of the stock returns arises from participating firms' higher carbon risk exposure

TABLE A2 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Basse Mama and Mandaroux (2021)	• International • 2005–2017 • 287 firms	Emission allocation and compensation mechanisms	• Stock market valuation (1-year-ahead)	• Total verified emission (TVE) European Union allowance (EUA)	• An inverted U-shaped association is found between carbon emissions (TVE, EUA) and future stock market valuation. The future market valuation initially increases with carbon emissions until a certain threshold of emission level and then decreases thereafter • This concave relationship exists for smaller firms with lower institutional ownership and lower analyst coverage
Bolton and Kacperczyk (2021)	• US • 2005–2017 • 3421 firms	N/A	Stock return	• Carbon emissions • Growth in carbon emissions	• Carbon emissions (and growth in carbon emissions) generate a positive impact on stock returns • This positive effect indicates that investors are compensated for their carbon risk exposure
Bose, Minnick, et al. (2021)	• International • 2006–2018 • 841 firms	• Institutional investor ownership mechanism • Analyst coverage mechanism	CAR	• Carbon emissions • Carbon intensity	• Cross-border acquisition announcements create higher CARs for high carbon-emitting acquirers to acquire targets in undeveloped countries. This suggests that acquirers move their carbon risk offshore to countries with weaker governance and regulations, thereby reducing carbon emission-related financial risk • Investors penalise acquirers that promote corporate social responsibility but have a higher level of carbon emissions, resulting in worse abnormal returns
Choi and Luo (2021)	• International • 2008–2015 • 1748 firm-year observations	Corporate governance mechanisms	Market value of equity(Ohlson's, 1995 model)	Carbon emissions	• Carbon emissions negatively impact firm valuation • This negative effect is more prominent for firms in countries that impose stringent environmental regulations and adopt a carbon emission trading scheme • The negative effect also becomes weaker for firms with better corporate governance, as well as those in countries with long-term orientations and high uncertainty avoidance

(Continues)

TABLE A2 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Choi et al. (2021)	• Australia • 2009–2015 • 522 firm-year observations	• Signalling theory • Voluntary disclosure theory	Market value of equity (Ohlson's, 1995 model)	Carbon emissions (direct)	• Direct carbon emissions negatively impact the market value • This negative impact becomes stronger when the Australian carbon trading scheme took effect • This negative effect is also noted for firms with lower scores on carbon disclosure or carbon management performance
Ramelli et al. (2021)	• International • 2018–2019 • 4244 firms	N/A	CAR	Carbon intensity	• A significantly negative relationship is found between carbon intensity (industry-level and firm-level) and CAR during the first global climate strike on 15 March 2019 • The negative effect on the market value of carbon-intensive firms suggests increased public awareness of climate activism

Abbreviation: CAR, cumulative abnormal return.

TABLE A3 Effects of carbon risk on the cost of capital.

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Li et al. (2014)	• Australia • 2006–2010 • 1050 firm-year observations	Informational asymmetry theory	• Cost of debt • Cost of equity	• Carbon emissions-liable (dummy) • Carbon emission intensity	• Carbon emissions-liable firms are likely to have a higher cost of debt and cost of equity • Carbon emission intensity positively impacts the cost of debt, whereas it does not affect the cost of equity
Kim et al. (2015)	• Korea • 2007–2011 • 379 firms	Portfolio theory	Cost of equity (Easton's, 2004 model; Ohlson & Juettner-Nauroth's, 2005 model)	Carbon emission intensity	• Carbon emission intensity is positively associated with the cost of equity • This positive association exists regardless of whether firms voluntarily disclose sustainability reports or not
Jung et al. (2018)	• Australia • 2009–2013 • 255 firm-year observations	• Agency theory • Carbon pricing mechanism	• Cost of debt • Default risk (robust test)	• Carbon emissions (Scope 1) • Carbon risk awareness (dummy)	• Carbon risk positively affects the cost of debt. This relationship is mitigated (or even reversed) for firms with greater carbon risk awareness • Carbon awareness is important for both carbon emitters in the business strategy development and lenders facing client default and reputational risk
Zhou, Zhang, et al. (2018)	• China • 2011–2015 • 191 firms	Agency theory	Cost of debt	Carbon risk (ordinal variable)	• A non-linear (U-shaped) association is found between carbon risk and the cost of debt • This association is predominantly found in private but not in state-owned firms • This association can also be mitigated through better media attention
Bui et al. (2020)	• International • 2010–2015 • 4655 firm-year observations	• Agency theory • Legitimacy theory • Ethical investing theory • Resource-based perspective	Cost of equity (Easton's, 2004 model; Ohlson & Juettner-Nauroth's, 2005, model)	• Carbon emission intensity • Carbon disclosure (score)	• Carbon emission intensity positively impacts the cost of equity, which is mitigated by carbon disclosure • Investors would consider the joint influence of carbon risk and carbon disclosure in assessing firm risk
Caragnano et al. (2020)	• International • 2010–2017 • 592 firms (3642 firm-year observations)	N/A	Cost of debt	Carbon intensity	• Carbon emission reduction positively impacts the cost of debt financing • Borrowers that have higher GHG emissions are required to pay higher costs to finance their business, which can reduce the impact on lenders' future cash flows

(Continues)

TABLE A3 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Palea and Drogo (2020)	• International • 2010–2018 • 1469 firm-year observations	Legitimacy theory	Cost of debt	Carbon emission intensity	• Carbon emission intensity significantly and positively affects the cost of debt • Prior to the Paris Agreement, high carbon emitters are charged a carbon risk premium, but low emitters are charged only following this • After the Paris Agreement announcement, climate-related disclosure of higher emitters could reduce the effect of carbon emissions on the cost of debt
Ehlers et al. (2021)	• International • 2005–2018 • 567 firms (1469 firm-year observations)	N/A	Margin of syndicated loan	Carbon emission intensity (Scope 1 and Scope 2)	• Carbon intensity does not impact the loan margin, suggesting that the loan margin is driven predominantly by loan characteristics, such as term spread, credit ratings and maturity, rather than by carbon risk • Following the Paris Agreement, Scope 1 emissions are still a bank's primary focus in loan lending, while Scope 2 emissions present a significant and positive effect, indicating a narrow view of a bank on carbon risk
Gerged et al. (2021)	• UK • 2011–2016 • 406 firms (1832 firm-year observations)	Targeted disclosure cycle theory	Cost of equity (Easton's, 2004 model)	• GHG disclosure (GHGD: Scope 1 and Scope 2 GHG emissions) • GHG emission squared	• A U-shaped association is presented between GHGD and the cost of equity • That is, GHGD negatively affects the cost of equity up to a turning point, and then, any increase in GHGD probably increases the capital of equity
Kleimeier and Viehs (2021)	• International • 2267 loans • 2009–2016	N/A	Loan spread	• Carbon emissions • (direct and indirect)	• A firm's loan spreads and a borrower's carbon emissions are positively related • This positive effect exists for all lenders, indicating that environmental risk primarily drives the loan spread premium rather than investor preferences
Morrone et al. (2021)	• US • 2003–2016 • 882 firm-year observations	N/A	• Cost of debt • WACC	• GHG emissions (direct and indirect) • • GHG emission intensity	• Both the level and intensity of emissions positively impact the cost of debt and WACC • Financial stakeholders should include the firm's environmental impacts when assessing their investments, especially within the energy sectors

Abbreviation: WACC, weighted average cost of capital.

TABLE A4 Effects of carbon risk on risk profiles (measures).

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Capasso et al. (2020)	• US • 2007–2017 • 485 firms	Option pricing theory	Distance-to-default (DD)	• Carbon emissions • Carbon intensity (Scope 1)	• DD is negatively correlated to carbon emissions and carbon intensity • The carbon footprint decreases DD following the announcement of the Paris Agreement • A firm's creditworthiness is impacted due to exposure to climate risk
Monasterolo and De Angelis (2020)	• International • 2015 • Not clearly mentioned	N/A	Market model: • Systematic risk (beta); • Paris Agreement announcement (dummy)	N/A	• After the Paris Agreement announcement, the systematic risk of low-carbon equity indices declined, suggesting that stock markets have priced this announcement by penalising carbon-intensive asset classes but rewarding low-carbon ones
Ilhan et al. (2021)	• US • 2009–2016 • S&P 500 constituents	Cap-and-trade mechanism	• Implied volatility slope (SlopD) • Variance risk premium (VRP) • Model-free implied skewness (MFIS)	Carbon intensity	• At the firm level, carbon-intensive firms exhibit a higher SlopD and VRP, but not MFIS • At the sector level, the impact of carbon intensity on SlopeD remains but becomes weaker for both VRP and MFIS • Options markets price the uncertainty of climate policy. For more carbon-intensive firms, it is expensive to use options against tail risk • The impact of carbon intensity on tail risk could be amplified when the public has a higher climate change awareness
Kabir et al. (2021)	• International • 2004–2018 • 2785 firms	Stakeholder theory	• Distance-to-default (DD) • Other proxies of DD • Probability of default • Altman *Z* score	Carbon emission intensity (direct and indirect)	• A negative association is documented between carbon emissions and DD • The effect of carbon risk on default risk could be mitigated by firms' green initiatives and their environmental commitments • Carbon risk affects a firm's default risk through two potential channels, financial performance (ROA) and cash flow volatility

(Continues)

TABLE A4 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Neudorfer (2021)	• US • 16/05/2009–20/06/2009 • 63 firms	• Rational expectation theory • Extreme value theory	Event study: • Implied 5% value-at-risk ($VaR_{5\%}$) • Option implied conditional value at risk (CVaR)	N/A	• Oil and gas companies, regardless of size, are equally exposed to the carbon risk • A firm with a high level of fossil fuel reserve is likely to be exposed to high tail risk
Safiullah et al. (2021)	• US • 2004–2018 • 3116 firm-year observations	• New classical theory • Social contract theory • Stakeholder theory	• Credit rating (S&P issuer-level)	Carbon intensity (direct and indirect)	• Carbon emissions negatively impact credit rating • This negative effect is more significant with direct emissions • A firm's higher level of carbon emissions generates higher cash flow uncertainty, resulting in a lower credit rating
Tzouvanas and Mamatzakis (2021)	• US • 2005–2018 • 500 firms (from the S&P500 index)	• Neoclassical theory • Agency theory • Instrumental stakeholder theory • Legitimacy theory	• Systematic risk • Idiosyncratic risk • Total risk	Environmental performance (EP) (inverted GHG intensity)	• Firms with higher EP have higher systematic risk, but lower idiosyncratic risk • The total risk of firms with higher EP decreases, which particularly benefits from lower idiosyncratic risk • EP has a positive impact on the sharp ratio, but no significant effect on stock returns • Overall, investments in environmental stocks are paid off

Note: DD: a reverse measure of default risk.

TABLE A5 Financial effects of carbon disclosure.

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Kim and Lyon (2011)	• International • 2006 • 358 firms	• Voluntary disclosure theory • Corporate governance theory	CAR	• Carbon Disclosure Project (CDP) participation (dummy) • • Firm headquartered in the country ratifying the Kyoto Protocol (dummy)	• There is no systematic evidence that the firm's CDP participation can increase shareholder value • Following the Kyoto Protocol ratification of Russia, the CDP's participation could increase shareholder value. This indicates Russia's ratification increases regulatory pressures on GHG industries in the US and other non-ratifying countries • Investors reward CDP participants
Griffin and Sun (2013)	• US • 2000–2010 • 84 firms	Voluntary disclosure theory	Event and portfolio studies: CSRwire release relating to carbon emissions	N/A	• Voluntary carbon disclosure produces positive returns to shareholders • Smaller firms' shareholders benefit the most from voluntary carbon disclosure as they do not have other channels to access competing information
He et al. (2013)	• US • 2010 • 181 firms	Voluntary disclosure theory	Cost of equity (Easton's, 2004 model)	Carbon disclosure (score)	• Carbon disclosure negatively impacts the cost of capital • This negative effect becomes weaker for firms with better carbon performance, compared with the sample median
Matsumura et al. (2014)	• US • 2006–2008 • 550 firm-year observations	• Stakeholder theory • Voluntary disclosure theory • Natural-resource-based theory	Market value of equity	• Carbon emissions • Carbon disclosure (dummy)	• Carbon emissions (carbon disclosure) negatively (positively) affect firm value • Every firm is penalised by the markets for its emissions. An extra punishment is incurred for firms who do not disclose carbon-related information

(Continues)

TABLE A5 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Saka and Oshika (2014)	• Japan • 2006–2008 • 1094 firm-year observations	N/A	Market value of equity	• Carbon emission intensity • Carbon disclosure (mandatory, dummy)	• Carbon emissions (carbon disclosure) negatively (positively) impact the market value of equity • The positive effect of carbon disclosure on the market value becomes stronger when a firm has a higher level of emissions • Firms are strongly encouraged to reduce carbon emissions as well as disclose information on carbon emissions
Liesen et al. (2017)	• International • 2005–2009 • 433 firms (1756 firm-year observations)	• Stakeholder theory • Legitimacy theory	Portfolio analysis: The portfolio is constructed on four proxies: • Carbon disclosure (dummy) • Disclosure Completeness Index (score) • Carbon emissions • Carbon efficiency	N/A	• Stock portfolios constructed by buying stocks from firms that report carbon information (or have a high carbon efficiency) and selling stocks from firms that do not report carbon information (or have a low carbon efficiency) earn positive risk-adjusted returns • Portfolios' returns do not change significantly with firms' carbon emission levels • Financial markets value the quality of carbon disclosure
Krishnamurti and Velayutham (2018)	• Australia • 2006–2009 • 558 firm-year observations	Voluntary disclosure theory	• Stock price volatility • Stock liquidity	Carbon emission disclosure quality (score)	• Carbon disclosure is negatively (positively) related to stock price volatility (stock liquidity)
Zhou, Zhou, et al. (2018)	• China • 2010–2014 • 830 firm-year observations	• Principal-agent theory • Voluntary disclosure theory • Financial transparency mechanism	Agency cost (management expense ratio; total asset turnover)	Carbon disclosure (score)	• Carbon disclosure negatively impacts agency costs • It is not clear whether financial transparency can influence the association between carbon disclosure and agency costs

TABLE A5 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Albarrak et al. (2019)	• US • 2009–2015 • 584 firms (1737 firm-year observations)	Legitimacy theory	Cost of equity	Carbon disclosure (number of carbon-related tweets)	• Carbon disclosures negatively affect the cost of equity • Carbon-related information disseminated on Twitter could update a firm's information to investors in an efficient and timely manner, allowing investors to assess a firm's performance with lower uncertainty
Lemma et al. (2019)	• South Africa • 2010–2015 • 98 firm-year observations	• Legitimacy theory • Voluntary disclosure theory • Signalling theory • Stakeholder theory	• Cost of debt • Cost of equity • WACC	Carbon disclosure (score)	• A significantly negative correlation is found between voluntary carbon disclosure and the cost of equity and WACC. However, the cost of equity is not sensitive to disclosure as WACC • Carbon disclosure does not impact the cost of debt • Firms that have higher carbon risk tend to do better in disclosing information
Schiemann and Sakhel (2019)	• International Sample 1: • 2011–2013 • 717 firms (2142 firm-year observations) Sample 2: • 2011–2013 • 367 firms (906 firm-year observations)	• Voluntary disclosure theory • Information asymmetry theory	Information asymmetry (bid-ask spread)	Climate-related physical risk disclosure (dummy)	• Voluntary disclosure of physical risk reduces information asymmetry for firms regulated by the emissions trading scheme of the European Union

(Continues)

TABLE A5 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Alsaifi et al. (2020a)	• International • 2007–2015 • 977 firm-year observations	Resource-based view theory	Financial performance (index)	Carbon disclosure (score)	• Carbon disclosure generates a positive effect on financial performance • Firms actively engaging in voluntary carbon disclosures have strong competitive advantages and could achieve higher financial performance
Alsaifi et al. (2020b)	• International (firms in FTSE350 index) • 2009–2015 • 977 firm-year observations	Stakeholder theory	Event study: • CAR	• N/A	• Investors' response is negatively related to carbon disclosure announcements via the CDP • The response is more significant and negative for carbon-intensive firms. Moreover, small firms primarily drive this significant and negative response
Adhikari and Zhou (2021)	• US • 2005–2016 • 4078 firm-year observations	• Information asymmetry theory • Socio-political theory • Stakeholder theory • Voluntary disclosure theory	• Bid-ask spread • Share turnover • Price volatility	Carbon disclosure (dummy)	• Carbon disclosure significantly reduces the bid-ask spread and share turnover, but increases price volatility • Firms will experience higher information asymmetry if they choose not to disclose their carbon-related information, not respond to the CDP survey or only provide incomplete information
Downar et al. (2021)	• International • 2009–2018 • Not clearly mentioned	• Targeted disclosure cycle theory • Cap-and-trade mechanism	Gross margin	• Carbon disclosure (dummy: UK mandate) • Post-mandate of carbon disclosure (dummy)	• Mandatory carbon disclosures have no significant effect on a firm's gross margin, which suggests that firms disclosing carbon information do not experience significant increases in the cost of sales • No empirical evidence is found that carbon disclosure mandates could deteriorate firms' operating performance

TABLE A5 (Continued)

Author (year)	Sample (country, period, size)	Applied theory/ mechanism	Dependent variable	Independent variable	Main findings
(1)	(2)	(3)	(4)	(5)	(6)
Jiang et al. (2021)	• International • 2009–2015 • 6436 firm-year observations	• Legitimacy theory • Voluntary disclosure theory	Market value of equity	Carbon disclosure (dummy)	• Carbon disclosure generates a significantly positive impact on firm value • Firms are rewarded by disclosing high-quality carbon information
Siddique et al. (2021)	• International • 2011–2015 • 187 firms	• Signalling theory • Voluntary disclosure theory	• ROA • Tobin's Q	Carbon disclosure (score)	• Carbon disclosure negatively impacts ROA, indicating that the costs of carbon disclosure may have outweighed the benefits in the short term • Carbon disclosure positively affects Tobin's Q, suggesting that in the long term, firms would benefit from high-quality carbon information, which is highly valued by investors

Abbreviations: CAR, cumulative abnormal return; CDP, Carbon Disclosure Project; ROA, return on assets; ROE, return on equity; WACC, weighted average cost of capital.