

Annual Review of Environment and Resources
**Stranded Assets: Environmental
Drivers, Societal Challenges,
and Supervisory Responses**

Ben Caldecott,¹ Alex Clark,¹ Krister Koskelo,¹
Ellie Mulholland,² and Conor Hickey¹

¹Oxford Sustainable Finance Programme, Smith School of Enterprise and the Environment, University of Oxford, Oxford OX1 3QY, United Kingdom; email: ben.caldecott@smithschool.ox.ac.uk, alex.clark@smithschool.ox.ac.uk, krister.koskelo@ouce.ox.ac.uk, conor.hickey@ouce.ox.ac.uk

²Commonwealth Climate and Law Initiative, Oxford University Centre for the Environment, University of Oxford, Oxford OX1 3QY, United Kingdom; email: ellie@commonwealthclimatelaw.org

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Keywords

stranded assets, just transition, climate change, central banks, climate litigation, biodiversity

Abstract

Environmental factors, particularly those related to climate change, are stranding or could strand assets across different sectors and geographies with significant implications for economies, companies, financial institutions, communities, and workers. In this review, we focus on physical climate change, biodiversity loss, and litigation related to environmental factors as causes of stranded assets. We also review the emerging literature on the consequences of asset stranding for society before turning to some of the key supervisory responses that are emerging to ensure that stranded assets are measured and managed, particularly by financial institutions. These are among the areas of the stranded assets literature that have been growing most rapidly since 2015, and we focus on the literature produced since then.

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INTRODUCTION

Stranded assets are “assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities” (1, p. 2; 2). Although stranded assets can be caused by a wide variety of factors and are a feature of the creative destruction seen in economic systems, a significant amount of recent attention has focused on how environment-related factors, particularly those related to the climate crisis, could strand assets across different sectors and geographies and what this could mean for economies, companies, financial institutions, communities, and workers.

Much of the literature has focused on two related concepts: unburnable carbon and the carbon bubble. Unburnable carbon is one driver of asset stranding and is the disconnect between the current value of global fossil fuel assets and their lowered commercialization potential under a strict carbon budget constraint (2–5). The idea that unburnable fossil fuel reserves could become stranded assets sparked a significant discussion on the risk of investing in fossil fuels and has also spurred the development of the fossil fuel divestment campaign (2, 5–7).

Conjoined and in parallel with this, the idea of a carbon bubble has also gained traction. The carbon bubble is a consequence of asset stranding and is the hypothesis that unburnable carbon resulting in significantly overvalued fossil fuel assets has created a financial bubble with potentially systemic implications for the global financial system (2–4).

In previous *Annual Review of Resource Economics* articles, van der Ploeg & Rezai (8) cover unburnable carbon, its causes, and economic costs, and Monasterolo (9) reviews the carbon bubble and how the financial system is exposed to climate-related financial risks. In this article, we focus on the causes of stranded assets beyond unburnable carbon not covered in the other reviews, such as risks related to physical climate change, biodiversity loss, and litigation related to environmental factors. We then review the emerging literature on the consequences of asset stranding for society before turning to the key supervisory responses that are emerging to ensure that stranded assets are measured and managed, particularly by financial institutions. Together these are among the areas of the stranded assets literature that have been growing the most quickly in recent years, and they may turn out to be as important for society, if not more so than some of the earlier literature. We focus on the literature produced since 2015.

RISKS RELATED TO PHYSICAL CLIMATE CHANGE, BIODIVERSITY LOSS, AND LITIGATION

Although much of the previous literature on stranded assets focuses on investments and assets directly related to fossil fuels and carbon emissions, such as coal power plants and oil and gas

Stranded assets:

assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities—a meta-definition

Unburnable carbon:

the stranded fossil fuel assets caused by the hypothesized enforcement of a strict carbon budget constraint

Carbon bubble: a

hypothesized financial bubble caused by the scale of exposure to unburnable carbon in the global financial system

reserves, this review emphasizes the impacts of environmental change on a much broader range of assets. Even if emission mitigation efforts succeed, further stranded asset risks are likely to arise as a consequence of physical climate impacts and ecological degradation (e.g., of arable land and coastal regions) (10) with widely varying impacts on different sectors (11). These other categories of risk, such as physical climate risk, climate-related litigation risk, and risk of biodiversity loss, have tended to receive less attention. This is true not just in the academic literature but also in firms, financial institutions, and, to a lesser extent, supervisory bodies. For instance, Goldstein et al. (12) assess the (in)sufficiency of private sector companies' approach to physical climate risk and adaptation, finding that companies systematically underestimate the costs of physical climate risks, and that only 21% report quantitative estimates for its anticipated effects on them.

Nonetheless, the impacts can be huge. One prominent estimate of the effects on global financial assets from physical climate impacts alone (direct impact and residual damages) put the mean value at risk in a business-as-usual scenario at 1.8%, or US\$2.5 trillion, by 2100, with a worst-case 99th percentile scenario placing 16.9% of assets at risk, or more than US\$24 trillion (13). The latter case would constitute a substantial write-down of all global economic assets. Estimates for losses from natural capital degradation and biodiversity loss are also of substantial magnitude. Between 1992 and 2014, while the value of produced capital (e.g., goods, factories) and human capital increased globally on a per capita basis, natural capital is estimated to have fallen by almost 40% (14). Estimates suggest that between 1997 and 2011, the world lost US\$4–20 trillion annually in ecosystem services due to changes in land use and US\$6.3–10.6 trillion annually from land degradation (15, 16).

Physical Risk

Historically, discussion of stranded assets in relation to unburnable carbon and to fossil fuel assets has fallen squarely under one type of climate-related risk: transition risk, which results from the economic and societal changes required to transition to a sustainable economy with net-zero carbon emissions. But an equally important source of climate-related risk capable of stranding assets is physical risk, driven by the physical (weather-related) impacts of climate change. For an overview schematic that compares the two, see **Figure 1**.

Climate-related physical risks are defined as risks to assets, companies, or portfolios resulting from physical weather phenomena caused or exacerbated by climate change (17). These risks can strand individual assets the counterparty owns, such as a warehouse destroyed by floods, and affect counterparties' operations through impacts on supply chains, regional/public infrastructure, or effects on other parts of the economy (e.g., stranded labor).

Physical risks manifest from a combination of physical hazards—that is, weather or climate phenomena; exposure, that is, assets located in a hazard zone and their upstream and downstream implications (e.g., effects on the corporations that own them or through supply chains); and vulnerability, that is, the extent to which a particular asset is at risk.

Hazards. There are a wide variety of physical climate hazards, usually classified as either chronic or acute. Chronic hazards include slower-moving changes, such as temperature rise and sea-level rise, whereas acute hazards are defined as severe weather events whose incidence is being increased by climate change, such as floods, hurricanes, heat waves, droughts, and wildfires (18, 19). Although physical risks are expected to worsen going into the future, physical impacts attributable to climate change are already manifesting themselves (20). One recent study finds that average river peak flood volumes in parts of northwestern Europe have already increased by up to 17.8%, relative to the 1960–2010 mean (21), while another concludes that increased outburst flood

Climate-related litigation risks:

climate-related risks leading to litigation to assign blame for the creation or materialization of these risks, and seeking damages

Climate-related physical risks: caused by physical weather phenomena resulting from, or exacerbated by, climate change

Chronic hazards: climate hazards from slower-moving changes, such as temperature rise and sea-level rise

Acute hazards: severe weather events whose incidence is being increased by climate change, such as floods, hurricanes, heat waves, droughts, and wildfires

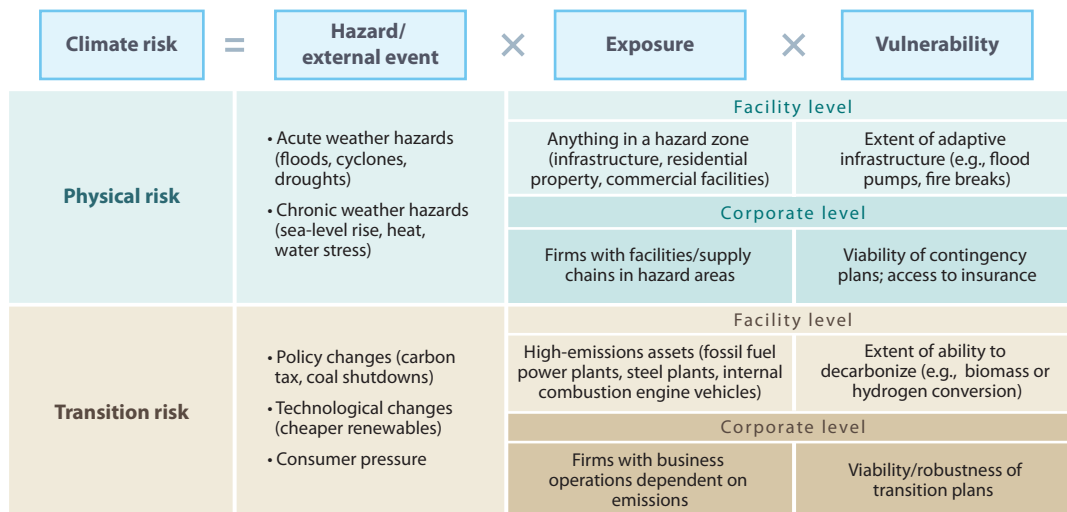


Figure 1

Constituent components making up the two main types of climate change risk: climate-related physical risk (from the physical impacts of changing weather and climate) and climate-related transition risk (from the economic transition associated with tackling climate change). Both result from a combination of hazards/external events, exposures, and vulnerability. Original figure based in part on the framework developed in 17 and 18.

hazards from Lake Palcacocha in Peru caused by glacial retreat are attributable with near certainty to anthropogenic temperature increases (22). Many of the physical impacts of climate change will be severe even if the most ambitious international targets of keeping warming to 1.5–2°C are reached (and substantially worse with 3–4°C of warming). In addition, due to lags in climate system responses to anthropogenic emissions, a certain amount of warming and the attendant physical impacts through the mid-twenty-first century is already “baked in” by existing greenhouse gas stocks, even if emissions rates were to decline to zero immediately (23).

Meaningful and accessible data on hazards can be hard to obtain. For some of these hazards, historical and observational data, and associated projections, are available but not easily accessible or useable. For others, there remain deep uncertainties and meaningful data and projections are unavailable. Most analyses use as a starting point the Coupled Model Intercomparison Project climate models used in the reports of the Intergovernmental Panel on Climate Change (IPCC) (24), but there are large differences between the various global climate models’ estimates to 2050 (23). Downscaling these global models to derive regional or local estimates further reduces precision. Moreover, many physical hazards do not manifest due to weather alone, but through interactions with local environmental factors. Wildfire risks depend not just on drought conditions but also on forest cover. Flooding impacts relate not just to extreme precipitation but also to topography and flood defenses, which vary by river basin. Additionally, for projections of future climate hazards to be useful, they need to be available over appropriate time horizons depending on the use case. Levels of granularity and geographical coverage also vary, and not all data are available at required confidence levels.

There are efforts under way to make climate hazard analysis more easily accessible. One example of a platform relating to a specific hazard (sea-level rise) is that run by Climate Central. The platform displays areas expected to lie below average annual flood levels in 2050 (25). Another example is OS-Climate, an initiative building a publicly available open source platform of

data and analytics for analyzing transition and physical risk, in collaboration with a range of financial institutions. The initiative applies a community-based open source approach similar to that underpinning the Linux operating system (26).

Exposure. Although some early physical risk approaches analyzed exposure at a country level (27), both commercial and academic approaches to measuring physical risks for the financial industry have since converged on the understanding that exposure requires overlaying climate hazard risk data and projections with geolocated asset-level data (18, 28, 29). Asset-level data can be found in many different locations. They can be found in existing company disclosures to financial markets, regulators, and government agencies (in multiple jurisdictions and in different languages); in voluntary disclosures; in existing proprietary and nonproprietary databases; in public and private research institutions; and in academic research (30, 31). The challenge is finding the relevant sources, integrating the data, cleaning the data, and then making the data available for analysis. In addition, there is significant and exciting potential for new information from big data, open source databases and remote sensing to complement these existing datasets (29, 32). The ability to directly observe and assess assets owned by listed and nonlisted companies is increasingly possible at progressively lower cost, even for companies unwilling to disclose them.

Some financial institutions may already have the asset-level data they require to overlay with climate hazard data, for example, a bank providing mortgage loans. However, the vast majority of financial institutions do not have access to asset-level data for more general counterparty analysis, such as all the facilities owned by, for example, a large multinational firm requesting a loan (let alone all the suppliers it is reliant on and their facility locations). This is even more challenging for entire portfolios, e.g., one comprised of shares or bonds in many large firms. This gap is being filled both by commercial providers such as Trucost, which sells asset-level data, and by collaborative efforts including the GeoAsset Project, which aims to “. . .make accurate, comparable, and comprehensive asset-level data tied to ownership publicly available across key sectors and geographies” (33, p. 1). In an approach analogous to the Human Genome Project, GeoAsset ultimately aims to coordinate the collective production of universally trusted, transparent, and verifiable datasets of every asset in the global economy.

Importantly, although precise asset-level data are best suited for analyzing financial portfolios, they do not reflect exposure at a city or country level, which can be vast and wide-ranging. For instance, most of southern Vietnam, including all of Ho Chi Minh City, a metropolitan area of 20 million people, would be exposed to sea-level rise by 2050 (25). Recent analysis found that, although a 100-year flood in Ho Chi Minh City today would cause approximately US\$200–300 million in damage, this would rise to US\$500 million to 1 billion by 2050 without investment in adaptation measures. A flood in 2050 would also have 20 times the estimated economic knock-on effects of a similar-sized flood today, including partial metro closures affecting approximately one million trips (34). Remaining focused on Southeast Asia, an integrated assessment model projecting that Indonesia, the Philippines, Thailand, and Vietnam would face an annual climate-induced gross domestic product (GDP) loss of 2.2% by 2100, returned an estimate of 5.7% once nonmarket impacts related to health and ecosystems are taken into account (35). In low-lying Bangladesh, 900,000 people by 2050, or 2.1 million by 2100, could be displaced by direct inundation resulting from sea-level rise (36).

Vulnerability. Understanding the vulnerability of assets and counterparties to climate hazards generates perhaps the greatest data challenges, as it requires both more granularity and more qualitative detail. In essence, vulnerability refers to how prepared an asset is to withstand physical changes. At the asset level, this might mean that even two neighboring, otherwise identical

Asset-level data:
data about the characteristics of physical and non-physical assets tied to ownership information

factories in the same flood-prone area might be affected differently if one has better flood walls, basement pumps, or worker contingency plans; however, even the most ambitious asset-level datasets do not currently have this level of detail. At a company level, understanding preparedness implies assessing the quality of business strategies and management plans with regard to physical climate risks. Ideally it should be possible to extract this sort of data from annual company or sustainability reports, although many companies either do not report this detail or report only limited information. Furthermore, calculation methodologies and reporting formats are not standardized, resulting in information that is not comparable (even when using advanced natural language processing techniques to extract it). Instead, today's leading providers of physical climate risk data still rely on relatively crude approximations, such as sector-hazard tables with subjective scores (27, 37).

Analysis of vulnerability at broader scales, for instance at the level of a city or country, is by comparison well-developed, as it links closely to discussions on preparedness, adaptation, and resilience. From a financial perspective, the discussion is often focused on insurance, which has been touted as an important adaptation solution in the academic literature (38, 39), by nongovernmental organizations (40), multilateral development banks (41), and the IPCC (24). However, at the asset level, insurance can just as easily contribute to, rather than prevent, physical climate risk-related asset stranding, for instance through insurers refusing to renew coverage for assets in particularly vulnerable areas, as has already occurred for residential properties in certain wildfire-prone areas of California and Australia (42, 43).

Estimating the impact and potential for stranding from physical risk. Chronic physical climate hazards, despite their slower-moving nature, can cause significant damage and lead to severe risk exposure. For instance, it is estimated that rising sea levels could cost the world more than US\$14 trillion annually by 2100, if the 2°C target set by the Paris Agreement is missed (44). Assets at high risk of stranding from sea-level rise have been shown to already be priced at a discount by investors. Notably, coastal properties in the United States exposed to sea-level rise sell at an approximately 7% discount compared to similar matched properties that are not exposed. Properties that are exposed at a level of 1 ft (30 cm) of global sea-level rise sell at a 14.7% discount, on average. Properties that are exposed at 6 ft (180 cm) of sea-level rise—levels not expected to be reached for a century, perhaps longer—are nonetheless already trading at a 4.4% discount compared to similar, unexposed properties (45).

Acute hazards present no less of a danger. The BlackRock Investment Institute estimates that hurricane damage to properties could rise by as much as 275% by 2050 due to their higher frequency and intensity (46). The Business Continuity Institute and Zurich Group revealed that 35% of supply chains were affected by adverse weather in 2018 (47). One of Europe's most severe recent heat waves generated economic losses of nearly €13 billion, and such heat waves are becoming more frequent (48). Damania (49) finds that there is strong evidence that floods and droughts can also have differential and significant impacts on particular components of the global economy, such as agriculture, human capital, and even defense and conflict.

Recent research suggests that if these potential impacts of physical risks—which create stranded assets—are unmitigated, they could propagate into stability concerns for the financial system (13, 50). For example, increasing climate-related physical risks can create increased exposure for insurers who underwrite policies on assets susceptible to physical risks, and insurers may in turn refuse to insure them as potential stranded assets (51). If these assets are uninsured, the deterioration of the balance sheets of affected households and corporations could lead to losses for banks and investors (52). As we move further into the twenty-first century, climate change is also likely to contribute to a greater likelihood of compound events, where two (or more) climatic events combine to produce an outcome that is worse than the effect of one of them

occurring individually. This could increase asset price volatility and demonstrates the likelihood that climate change will be nonlinear in its impact on economies and investment returns.

Within portfolios, investors are exposed to a range of sectors and geographies, each of which will be affected differently by physical climate change impacts now and in the future. For example, physical risk exposure within some sectors, such as technology hardware and equipment manufacturing [an industry deeply affected by climate change–induced floods in Thailand in 2011 (53)], is expected to be much higher than in others, such as professional services. No sector or geography can be considered immune from physical risks, but vulnerability and resilience will vary considerably (24, 50, 54).

Pension funds are exposed to physical risks due to their ownership of individual assets and companies, as well as through their role as large investors in particular regions and often as universal owners exposed to general macroeconomic conditions. Many investors have large, diversified portfolios, so their performance is partly reliant on the performance of the economy as a whole, and this is likely to be negatively affected by climate change if business as usual continues and physical risk causes sustained damage and disruption across multiple sectors and regions (55, 56).

The magnitude of the climate impact on global and regional economic growth depends on the level of global warming. In high temperature scenarios (i.e., $> +4^{\circ}\text{C}$), physical climate change impacts could have catastrophic impacts on the global economy through damage to property and infrastructure, loss in productivity, disturbance of international trade, food and water shortages, mass migration, as well as insecurity and conflict (56). The damage caused by climate change to global annual economic output and systems is nonlinear, with damages expected to increase slowly at low temperatures but then disproportionately proliferate with increasing temperatures (24, 57, 58). This could be accentuated if the Earth system passes tipping points, whereby human-induced climatic shifts can generate positive feedback effects, potentially causing a severe, global, and irreversible breakdown of climate system stability.

Improving physical climate risk analysis to be able to better inform decision-making across the financial system presupposes more and better data, disclosure, analysis, and projections for climate hazards, exposures, and vulnerabilities. The following will eventually be needed: a wide variety of material physical climate hazard data and projections, covering appropriate time horizons with levels of granularity, geographical coverage, and confidence relevant for financial institutions; comprehensive, consistent, and comparable physical asset-level data by sector tied to ownership in order to assess exposures to the above hazards; and an understanding of the vulnerability of assets and counterparties, measured both by asset-level assessments and through examining the quality of business strategies and management plans to manage climate-related risks, as well as measures of resilience.

If financial institutions are to grapple with and address physical climate risk, they will require better data and analytical capabilities. Progress will only occur if different parts of the financial system adopt and implement physical climate risk analysis in practice, ranging from banks to asset managers to asset owners—not just insurers, which have been the principal type of financial institution dealing with physical risk so far. Importantly, data on direct and indirect climate impacts are not necessarily enough, as firms can also be held legally liable for the physical impacts of climate change (e.g., through their contribution to emissions or through failure to adequately manage anticipated impacts), leading to liability risks, which can be hard to quantify.

Litigation Risk

Among climate risks, both physical and transition risks have the potential to lead to litigation meant to assign blame for the creation or materialization of these risks and seek damages. Broader

environmental risks can also lead to litigation (see below on biodiversity-related liability risks). Firms can be held liable, and as a result firms and assets can be subject to liability risks. Due to their unique status as a product and function of physical or transition-based risks, some analyses consider liability risks as a subset of these categories (59), whereas others analyze them separately (60). This review follows the latter approach and defines liability risks as resulting from (a) mismanaging, (b) misreporting, or (c) causing climate change.

Liability risks have the potential to act as both a driver and a consequence of the physical impacts of climate change and of the transition to a net-zero economy, as explained in research by law firm MinterEllison and think tank 2° Investing Initiative (61–63). Litigation can lead to many outcomes giving rise to stranded assets: fines or penalties, class action damages, legal costs, changes in valuation, changes in credit ratings, reputational damage, market exclusions, direct regulation, asset confiscation, and restriction of insurance. It can also have other, more indirect internal costs for firms, such as management distraction and staff morale. For those cases where assigning liability requires attribution of the defendants' emissions to the claimant's harm, the magnitude of these climate damages could be substantial. One example are traditional climate damages cases against carbon majors, that is, firms such as oil and gas firms that are responsible for large amounts of carbon emissions. Not all climate-related liability arises from attribution, as defendants may be liable for a failure to manage or disclose climate risks that have nothing to do with their own emissions, such as the potential liability for directors' duties.

For financial markets, climate-related liability risk is particularly difficult to assess and price in advance. Climate litigation is grounded in multiple interacting, evolving natural and human sources and systems, including legal, financial, and biophysical systems. This is compounded by various factors and elements particular to litigation. First, litigation has a behavioral element—potential claimants must decide if, when, who, and how to sue. Second, climate litigation is not one type of case or a feature of one jurisdiction. The 1,600+ cases filed by the end of 2020 represent countless legal theories, harms, causes of action, jurisdictions, and relief sought. Even for similar factual scenarios and causes of action—for example, suits for climate damages against carbon majors—courts in different jurisdictions have ruled differently on issues of liability (64).

Duties of trust, loyalty, and care. On a fiduciary basis, company boards not only can consider climate change-related issues but likely must do so, in the same way as they would any other material financial risk issue, according to research by the Commonwealth Climate and Law Initiative (CCLI) (65). A duties-based consideration of climate change focuses on whether the directors have exercised due care and diligence in considering this issue in their pursuit of the company's/members' best financial interests. In the United Kingdom, for example, a breach of the duty to promote the success of the company may result from a defect in the decision-making process where a director fails to have regard for the impact of the company's operations on the community and the environment, and where those factors impact the interests of the company (66).

Australian barrister Noel Hutley SC concluded in a 2016 legal opinion that as a matter of Australian law “climate change risks are capable of representing risks of harm to the interests of Australian companies, which would be regarded by a Court as being foreseeable,” and “may be relevant to a director's duty of care to the extent that those risks intersect with the interests of the company” (67, p. 2). In 2019, Hutley SC updated the legal opinion, concluding that there has been a demonstrable shift in the way in which Australian regulators, firms, and the public perceive climate risk, which “elevate[s] the standard of care that will be expected of a reasonable director” in discharging their duty of care (68, p. 2). In August 2019, Lord Sales, Justice of the UK Supreme Court, went further in a speech on directors' duties and climate change, noting that

general fiduciary and duty of care obligations may require directors to have regard for climate-related risks and to take action to reduce their contribution to climate change (69).

What these duties require as a matter of good governance and prudent risk management is constantly evolving, in line with changes in knowledge, regulation, and market practice. As the CCLI and ClientEarth explain in a C40 cities toolkit to fossil fuel divestment (70), a reasonable decision for a director or trustee fifty, ten, or even five years ago might not appear so reasonable today. This is particularly relevant in the case of climate change, where evidence of climate-related risks and opportunities are becoming ever more apparent, regulation is gathering pace, and the likelihood of a disorderly and disruptive transition increases. To discharge their duties, therefore, directors and trustees would have to integrate climate risks and opportunities into their governance roles.

Climate change attribution science. Attribution science is a set of methods, primarily using counterfactual inquiry, to identify and quantify a change in the probability or intensity of an extreme weather event or other climate-related phenomenon, such as a heat wave or glacial ice melt, due to human influence on the climate (71). This can tell us how much climate change is to blame for extreme weather events. In some cases, it increases the frequency or magnitude of an event or the event's impacts (i.e., the damage). In a few cases, scientists have found weather events that could not have happened in a world without human-induced climate change (72).

By calculating the influence of climate change on the weather, attribution science offers evidential tools to assess legal concepts of causation and responsibility. According to research of this type, the Australian wildfires of 2019–2020 were made at least 30% more likely by climate change, and the Thai floods of 2011 would probably not have occurred without human-induced climate change (53, 73). The Siberian heat wave in the first half of 2020, where a high temperature of 38°C was recorded above the Arctic Circle at Verkhoyansk in June 2020, makes for a particularly stark example: Researchers found the prolonged heat was made at least 600 times more likely by climate change (74).

Attribution science can help establish a causal relationship between defendants' emissions and plaintiffs' losses (75, 76). To date, few cases have used peer-reviewed attribution science evidence, which has constituted an obstacle in establishing legal causation. This presents opportunities for high-quality science to assist the courts in determining liability, particularly in claims for causing climate change, as discussed below. It is also now scientifically possible to attribute damage arising from climate change to certain greenhouse gas emitters. This began with a landmark 2014 study by Richard Heede (77) finding that almost two-thirds of carbon dioxide and methane emitted between 1854 and 2010 is attributable to just 90 private and state-owned entities, labeled carbon majors. This research has since been expanded and updated as part of the Carbon Majors Database (78). This combination of attribution science and historical emissions contributions has been proposed as a basis for establishing legal causation and awards of damages by the courts.

However, there are numerous challenges. Although general causation is usually accepted by the courts (i.e., that the defendant's emissions cause climate change), many difficulties remain in establishing specific causation (that the defendant's emissions caused the climate-related losses of the plaintiff) (79). Natural climate variability means that it is usually not accurate to say that events are 100% attributable to climate change. Fungibility of greenhouse gas emissions means it is also inaccurate to say that the loss is 100% attributable to the defendant.

An exploration of climate lawsuits. Below are examples of claims brought or liabilities realized to explore climate litigation and liability risks across the globe. The financial consequences of these claims to the defendant, such as the damages, penalties, and loss of insurances described above, can transmit through the financial system, for example, to insurers where the defendant's

compensation order is covered by insurance, or to banks, where its customers' litigation creates credit risks and reduces the bank's asset prices for its loans to the customer.

Mismanagement. In recent years, lawsuits have been brought alleging the mismanagement of physical or transition risks to an affected entity. *Conservation Law Foundation v. Shell* is a claim against an infrastructure owner for failing to manage physical risks. The US nonprofit Conservation Law Foundation filed a complaint in 2017 against Shell claiming it has failed to satisfactorily prepare its Providence Fuel Terminal for sea-level rises and the increased frequency and intensity of severe weather events (73). The litigation is ex ante of the physical risk, indicating that liability risks can bring forward the materiality of the physical or transition risks on which they are a product and function. Other liability risks can occur ex post the relevant climate risk. In the case of *Trotter (Trustee of the PG&E Fire Victim Trust) v. Chew et al.* (2021) (80), the directors and officers of Californian utility PG&E have been sued for breach of fiduciary duty for alleged mismanagement and misleading disclosures relating to the maturity of the company's wildfire risk management programs. This has been described as “the first climate-change bankruptcy,” as it occurred following the materialization of physical risk in the Californian wildfires of 2017 and 2018 (81).

Although these claims demonstrate that liability risks to entities go beyond the archetype of climate litigation against carbon majors for causing general climate change, many of the initial targets are in the same emissions-intensive sectors. This is demonstrated by *ClientEarth v. Enea*, a shareholder stranded asset claim against a Polish utility. In 2018, ClientEarth brought shareholder proceedings in civil law jurisdiction Poland against Enea, alleging a failure to consider the material economic transition risks of its project to build the €1.2 billion Ostrołęka coal-fired power plant. ClientEarth had also put the directors on notice in relation to a breach of directors' duties (82). Although the proceedings were brought by a nonprofit, analysts had said that the project would be a financial disaster for the company, there were warnings of a credit ratings downgrade, and institutional investors expressed serious concerns about the project. In 2019, the Poznań District Court handed down a landmark decision that found in ClientEarth's favor on the first ground (the board resolution approving the power plant was legally invalid under company law), precluding a need for the judge to formally determine the second ground (climate risk) (83).

Mismanagement claims extend beyond emissions-intensive sectors and upstream into the investment chain. In *McVeigh v. REST*, an Australian pension fund member sued the corporate trustee of his pension fund, alleging a breach of the duties of the fund's corporate trustee to act with due care, skill and diligence, and to act in the 23-year-old member's best interests (84). The claim alleged that to fulfil the trustee's legal duties, it was necessary to have regard for the Task Force on Climate-related Financial Disclosures (TCFD) recommendations for climate risk management and reporting. The parties reached a settlement just prior to the scheduled start of the hearing in November 2020 (85). Although this means there is no formal precedent in this climate risk fiduciary duty case, the terms on which the parties agreed to settle illustrate how high the standard of due care and diligence in this area has become. REST acknowledged the risks climate change poses to its own fund, making an ongoing commitment to develop the systems, policies, and processes to ensure these climate risks are identified, mitigated, and managed in line with the goals of the Paris Agreement, including a target for a net zero-emissions portfolio by 2050 (86).

Misrepresentation. Perhaps even more removed from the traditional climate damages cases is litigation for misrepresentation. These cases do not hinge on the actual emissions or climate impacts of the defendant, but simply on the veracity of disclosures relating to climate change and typically focus on the climate risks to the disclosing entity.

In *Abrahams v. CBA*, two shareholders of the Commonwealth Bank of Australia filed a suit claiming that it failed to adequately disclose the business risks climate change poses to the financial position and performance of the bank, including risks from the bank's potential investment in the Adani Carmichael coal mine (87). The plaintiffs withdrew the suit after the bank disclosed the relevant risks in their 2017 annual report. The bank has since improved in the sophistication of its TCFD disclosures year-on-year and is regarded as a leader in its sector (88). *O'Donnell v. Commonwealth* involves a claim against the Commonwealth of Australia and a number of its officers by retail purchasers of exchange-traded government bonds alleging that the investor information statements are misleading or deceptive on the basis that they do not adequately disclose the economic and fiscal risks associated with climate change and associated credit risks to the bonds. The claim further alleges that, in approving the disclosure documents, two government officers failed to discharge their statutory obligation to exercise due care and diligence (89).

Companies operating in emissions-intensive industries have also been the target of misrepresentation claims. *ClientEarth v. BP* involved a greenwashing complaint against BP alleging violations of the Organisation for Economic Co-operation and Development (OECD) Guidelines. ClientEarth alleged that a BP advertising campaign misled its shareholders and the public by giving misleading impressions of the role of renewables in its business to portray its impact on the climate as favorable. The complaint did not proceed after BP withdrew its advertisements in February 2020 (90). The UK National Contact Point for the OECD Guidelines for Multinational Enterprises, however, still assessed the complaint as material and substantiated without issuing any judgment (91).

Causing climate change. Although litigation and liability risks extend beyond the traditional climate damages, this is the source of liability risk that is currently most salient to many companies and their banks and insurers. More than a dozen US cities and states have proceedings underway against oil and gas companies seeking compensation for their current and future costs of dealing with increased temperatures, rising sea levels, and other impacts of climate change (92). In essence, the claimants allege that defendants have substantially contributed to greenhouse gas pollution and climate change by extracting, producing, promoting, refining, distributing, and selling fossil fuel products, while simultaneously deceiving consumers and the public about the dangers associated with those products. If the cases survive initial legal questions of admissibility, the courts must wrestle with complex issues such as causation, standards of reasonableness, and whether liability should attach to the producers (the carbon majors) or the users of fossil fuel (the consumers, such as the plaintiffs themselves).

Although there have not been any damages orders to date for these types of claims, there is legal precedent that climate harms can in principle give rise to corporate liability. In *Lliuya v. RWE*, lodged in the German courts in 2015, a Peruvian farmer alleges that the historic emissions of German power utility, RWE, contributed to increased global temperatures, causing the glaciers around Lake Palcacocha to retreat and the lake to expand, with residents in the town below facing an increased risk of severe flooding. Based on the German law of nuisance, the claim alleges RWE is liable on the basis of its pro-rata contribution to the damage, using the carbon majors study, which attributes 0.47% of historic global emissions to RWE (93). The claim was initially dismissed by the lower court before a higher court held the claim was admissible, finding that the causal chain and the defendant's share of co-causation are measurable and calculable, allowing the claim to proceed to the evidentiary stage (94).

Biodiversity-related liability risks. Moving beyond climate risks, there is growing concern among central banks, regulators, and financial market participants about the stranded asset risks











Liability risks associated with		
1 Physical or ecosystem impacts	2 Transition to sustainable or regenerative economy	3 Misrepresentation of biodiversity risks or ecosystem impacts
<p> 1A Direct impact through failure to prevent biodiversity loss or ecosystem consequences</p> <p> 1B Indirect enablement through failure to prevent biodiversity loss or ecosystem consequences</p> <p> 1C Failure to manage or adapt to biodiversity-related physical risks or ecosystem dependencies</p> <p> 1D Failure to comply with regulatory requirements associated with biodiversity loss or ecosystem protection</p> <p> 1E Financier or advisor liability for investee conduct under 1A–1D above</p>	<p> 2A Failure to manage or adapt to biodiversity-related economic transition risks from policy, regulation, technology, or shifts in stakeholder preferences</p> <p> 2B Anti-biodiversity regulation claims disputing the validity or application of biodiversity-related regulation</p>	<p> 3A Market misrepresentation of material biodiversity-related risks in mandatory securities or other regulatory filings</p> <p> 3B Promotional misrepresentation or greenwashing of biodiversity-related impacts or credentials in advertising or promotion</p> <p> 3C Financier, advisor, or auditor liability for investee or client misrepresentations under 3A and 3B above</p>

Figure 2

Summary framework of biodiversity-related liability risks. These risks stem from (1) physical or ecosystem impacts (failure to manage or adapt to physical ecosystem impacts and ecosystem dependencies, or comply with regulatory requirements), (2) the transition to a sustainable economy (failure to manage or adapt to transition risks and contestation of the validity of regulations), and (3) misrepresentation of risk and impacts (in regulatory filings or promotional material). Figure adapted with permission from Reference 97.

associated with a loss of biodiversity and ecosystem services (see, e.g., 59, 95). Biodiversity-related liability and litigation are increasingly flagged by organizations such as the OECD and the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) as relevant issues, both in their own right and as mechanisms for the transmission of discrete physical and market-based risks across economic systems. It is prudent to take a forward-looking view of liability risks, as behavior today could enliven litigation in the future.

To date, biodiversity-related liability exposure has focused on environmental claims (96). Recent research by the CCLI (97) observes that it is not limited to prevailing categories of environmental law claims and proposes a framework to assist firms and regulators to assess these risks. The CCLI's framework sets out three high-level categories and 10 subcategories of biodiversity-related liability risks (see **Figure 2**). This framework shows that, like climate litigation and the associated liability risks, biodiversity-related liability risks will not be limited to damages claims for causing biodiversity harms. Instead, biodiversity litigation could extend to the mismanagement of the transition to a sustainable or regenerative economy, as well as misrepresentation of biodiversity risks or ecosystem impacts. This is because claims are expected as a consequence of the losses suffered from the human, ecological, and financial impacts of the five key drivers of biodiversity loss set out by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services: changes in land and water use, exploitation of organisms, climate change, pollution, and invasive alien species (98). Strategic claims are expected as claimants seek to stop the key drivers of biodiversity loss, as well as more traditional compensation-based claims following loss.

According to the CCLI (97), the magnitude of liability exposure as a biodiversity-related financial risk, and whether it is material to any given financial institution, system, or economy, can be summarized as a function of three factors: the nature and breadth of potential liability exposures through the myriad causes of action available, the transmission mechanisms within and between the real economy and the financial sector, and legal and market dynamics in the jurisdiction. Just like climate-related liability risks, understanding the range of potential biodiversity-related liability risks will enhance the position of financial institutions to identify, price, and mitigate these direct and indirect impacts and for financial regulators to integrate these risks into their supervisory activities under their financial stability mandates (97).

Although there are some similarities to climate litigation, there are key differences that have implications for the materiality of biodiversity-related liability risk. Claims relating to physical, localized biodiversity impacts may in fact face lower procedural and evidentiary hurdles than those seeking to attribute liability for climate change–related physical impacts, which are hampered by the spatial and temporal disconnect between the emissions and their harm.

Although climate litigation and biodiversity litigation are not new, there are two reasons to expect an increasing number of claims and therefore the potential for increasing materiality of liability risk. The first is because of strategic litigation where claimants use the courts to bring action on climate change and biodiversity. The second is the potential for losses of immense magnitude, which encourage actors—and particularly sophisticated commercial actors with resources or litigation funding—to seek compensation via the courts. This will have consequences for real economy actors, financial firms, investors, and supervisors already grappling with climate change and biodiversity loss and the transition to net zero and sustainable economy.

Consequences of Stranded Assets for Society

Beyond the courts, the diffuse benefits and visible, concentrated costs of asset stranding raise questions around balancing economic efficiency, fairness, and other political economy considerations when deciding who should bear these costs, requiring systematic analysis of the distributional impacts across the value chain, from extraction to final use (99). Equally important is understanding the influence of special interest groups and political power over determining how costs are, and could be, borne.

Efficiency. Predicting the trajectory of asset stranding pathways in advance is difficult and highly uncertain. This is partly because the counterfactual depends on, *inter alia*, price trends in clean technologies, time preferences, industrial structure, marginal climate co-benefits, and the ability of labor markets to adapt to shifting employment patterns. Existing computable general equilibrium (CGE) models struggle to capture these complexities (100). Although it is widely accepted that switching to low-carbon generation is a net job creator overall (101, 102), the distributional consequences are less clear. This makes it difficult for policymakers to identify and prioritize policy options that have a high likelihood of achieving an appropriate balance of economic efficiency and distributional equity.

CGE modeling does, however, suggest that policy instrument choice matters for how efficiently stranded asset costs are allocated. Using the power sector as an example, a socially efficient carbon price can cause existing assets to be retired earlier than planned and can generate significant private stranding costs. A second-best (in terms of social efficiency) feebate system that incentivizes green investment without accelerating fossil fuel phaseout could see the magnitude of stranded assets fall, but with some costs shifted to the general public. A phased-in carbon price also avoids early retirements, but still generates some asset stranding by inducing losses for asset owners. This

suggests that use of the latter instrument choices is a feasible means for governments to reduce stranding but requires transferring some private costs to the public balance sheet (103).

Examination of the implications of asset stranding in labor markets (i.e., stranded labor) focuses on ways of reallocating labor and knowledge to minimize transition costs. This research finds that segregation of skills across labor forces (within and between countries) can exacerbate the distributional consequences of stranding-induced labor market shocks (104). Research on China's economy, where stranding risks to coal-based infrastructure are particularly high, suggests that policies causing asset stranding generate labor shocks to carbon-intensive sectors including and beyond coal extraction (particularly those dominated by state-owned enterprises that also provide other social services) and can threaten social stability where concerns around unemployment, pensions, social security and medical care, relocation, and labor-government relations are inadequately addressed (105–107). Structural constraints (including specialization in high-carbon industries) and path dependency in the development and innovation of complex products imply that green production capabilities are cumulative, such that small, early shifts toward specialization in green products (supported by wage subsidies and unemployment insurance where appropriate) can reduce stranded labor risks, all else being equal. Because of this path dependency, latecomers to the transition may face greater difficulties in reorienting their economies to green activities without disrupting the growth needed to finance clean production (108), such that excessive stranding of dirty industry assets in the short term can be counterproductive if it hampers investment required to develop green production capacity.

Network-based analysis can help identify strategies for reducing stranding burdens by shifting labor and capital resources in high-carbon industries toward “green adjacent possible” low-carbon uses (109). The ability of economies to take advantage of these opportunities is highly context-dependent, however, and must be weighed against other available ways to avoid prolonging the life of existing capital assets and jobs. The case for reallocating physical and labor resources is strongest where investment in new zero-emissions infrastructure and associated skills is economically optimal. However, deliberately stranding privately owned assets may be very obviously socially beneficial, depending on how forms of capital are accounted for. Economic analysis of the Hambach lignite mine in Germany finds the net present gains from immediately halting operations are 13–30% of the region's GDP once accounting for natural capital. The study also finds that health savings from avoided pollution are six times the cost of replacement with renewable and storage alternatives, and more than 100 times the cost of compensating stranded workers (110), suggesting that the case for policy-induced stranding is overwhelming from a social cost/benefit standpoint.

Although significant attention has been devoted to quantifying fossil fuel subsidies (111) and analyzing the effects of delinking cross-subsidization of downstream industries (101), the revenue implications of asset stranding (downstream or upstream) are less well-explored. Central and local public budgets can depend heavily on tax and royalty revenues from high-carbon activity. Further work is needed to weigh the revenue forgone by asset stranding and associated unemployment and social security liabilities against ongoing subsidy costs, increased tax revenues, and lower health and climate burdens from low-carbon alternatives.

The economic stimulus measures adopted in response to the COVID-19 (coronavirus disease 2019) pandemic across every major economy and amounting to several years' worth of discretionary spending provide some insight into how governments facing political and fiscal pressures might handle stranded asset risks in the longer term (112). Pre-pandemic, some asset stranding (particularly in the power sector) was already considered largely inevitable, with most uncertainty revolving around the timeframe for stranding (113). Since then, sharp declines in long-term oil prices have seen industry profitability fall and have curtailed previously planned investment.

Expectations of stronger climate policies (114) have exacerbated these trends, with BP cutting its long-term oil price forecast to US\$55/barrel, which triggered a US\$17.5 billion write-down of its assets (115). Despite this, with few exceptions, fiscal stimulus measures have intensified carbon-growth linkages and supported industries exposed to stranding (116), generating larger potential stranded asset pools (102) and raising the proportion of losses likely to ultimately accrue to public balance sheets through increased public ownership of, or exposure to, affected firms (117). Unconditional bailout support for high-carbon industries (including aviation and shipping), for which decarbonization options are in development but not yet competitive, has seen firms recapitalized without any requirements to make progress toward these options, risking further investment in high-carbon assets (112). In developing economies, severe funding shortages make the consequences of wasting resources on high-carbon industries more severe, resulting in much larger mid-/long-term stranded asset risks and potentially dampening future growth (118). Stimulus packages focused on clean growth, such as the European Union's (EU's) recovery package, may accelerate the materialization of stranding risks by offsetting pandemic-induced declines in commodity prices favoring high-carbon asset owners, with investment in technologies essential to decarbonization (119) and progressive removal of the need for subsidies (120). If deployed appropriately, the EU package can also mitigate dislocation caused by asset stranding by redirecting investment toward expanding employment opportunities in clean industries (121).

Political economy. Political economy research is addressing how the costs of deliberately or indirectly stranded assets are borne and mapping how different interests compete in determining this allocation (122). Developed countries feature heavily in the literature (see, e.g., 123, 124) despite the more concentrated risks and political constraints faced by less diversified economies (125). For example, aggregate upstream asset stranding risks in large non-OECD economies are moderate overall but are concentrated in key sectors: coal in China and crude oil in the Middle East and Latin America. Although an eventual green transformation is considered more likely in China, vested interests and social contract disputes in all these regions are expected to hamper attempts to diversify away from stranding risks (126).

Stranded assets can be created deliberately through changes in regulation, but whether such regulation is implemented and what form it takes are subject to political gaming. Brennan & Boyd (127) suggest, for instance, that regulators subject to lobbying and political pressure may actually have less information on future regulation than those they regulate. This strengthens the case against compensating firms for adverse regulatory changes. However, failing to offer firms compensation for stranding-inducing regulation *ex ante* may incentivize them to oppose otherwise sensible policy proposals in the first place, potentially resulting in weaker regulation, or no regulation at all (127). These issues may be more or less prominent depending on the independence and power of regulators, and lobbies' influence over government policy (101). In the international trade arena, policies to preemptively strand assets can also be hamstrung by legal challenges brought by private firms under investor-state dispute settlement mechanisms (128). In intergovernmental affairs, some states have sought compensation for stranding their own assets; however, the experience of the Yasuní-ITT initiative in Ecuador, which unsuccessfully attempted to raise US\$3.6 billion in exchange for not developing Ecuadorian oil fields, suggests that few governments are willing to pay for others to strand resource endowments, partly over concerns that doing so might lead other countries to demand similar payments (129).

Firms have demanded compensation even when affected assets would have been retired anyway on economic grounds largely unrelated to climate policy (101). Germany's proposed coal phase-out policies compensate coal plants already considered economically unviable (130). Firms may also deliberately overinvest in risky assets on the expectation of future compensation (99).

In the United States, for example, regulatory incentives have historically been directed toward coal plant retrofits, pushing investment toward incremental efficiency improvements, instead of replacement with clean energy sources. Declining coal power generating hours (primarily due to competition from gas) have generated stranded costs for plant owners, in some cases leading state and federal governments to make payments to utilities to accelerate coal retirement in the form of accelerated depreciation or securitization payments (although utility-supported legislation to help recover stranded costs has not always succeeded, as in the case of Arizona bill HB 239, which resulted in the bankruptcy of a FirstEnergy subsidiary). These dynamics are also visible in Australia, where economic analysis suggests that further government subsidies to coal mines or transport risk wasting public funding and encouraging further private investment in assets at high risk of stranding (131).

The consequences of poor investments by regulated asset owners may also be allocated to ratepayers. In 2019, legislation in New Mexico required ratepayers to subsidize payments to the privately-owned PNM (Public Service Company of New Mexico) for accelerating the closure of its existing coal units (123). This precedent may pose a moral hazard for utilities investing in new gas plants today that are expecting electricity ratepayers, or the general public, to meet the cost of stranding them. Utilities could benefit doubly by using the proceeds of early retirement payments to finance, and profit from, clean energy investments (123). Under these conditions, it may be socially efficient (if politically unacceptable, particularly where firms knowingly caused unnecessary harm) for governments to purchase stranded assets at a discount and deliberately not exploit them (99). Notably, alternative models for addressing stranding risks are emerging among US community-owned co-operative utilities, in the form of coal-for-solar revenue swaps and securitization to lower the cost of retirements and substitute revenues with clean energy, a model that may yet expand to for-profit utilities as plants become more expensive to run and opportunity costs rise (132).

Policy credibility and the green paradox. Climate policy inconsistency (whether due to political upheaval or lobbying by industry) can also raise stranded asset risks. When governments cannot credibly commit to long-term future policies, they may also fail to generate the expected policy responses from firms. Firms facing non-credible climate policies are less likely to reduce stranded asset risk exposure, which may increase as action is delayed, the carbon budget constraint guiding future policy tightens, and the severity of future policies or other shocks rises. Investment taxes may present a time-consistent way of achieving emissions goals (133), although policy signaling that bars the use of public funds to compensate stranded assets, prior to policy implementation, may also help build political support, reduce the risk of policy reversal, and undermine pro-compensation lobbying (101). Simply labeling assets as stranded against fixed carbon budget benchmarks may be a way of providing sufficiently clear market signals on future policy to support shifts in capital away from affected assets and firms (134). In response, financial institutions could work with labor interests to speed retirement of high-carbon assets and codevelop closure plans that support worker retraining and redeployment. Such efforts may reduce the ultimate burden on governments to meet adjustment costs faced by polluting firms (135).

Vicious cycles in climate policy trajectories are also a risk in countries where declining power demand and renewable competition mean newer coal mines or plants will likely be economically stranded independent of climate policy (e.g., South Africa, Poland, and Australia). In such cases, short-term delays to climate policy may substantially increase the value-at-risk of stranded assets, inhibiting the political feasibility of either compensating firms for asset stranding with public resources or forcing the materialization of stranding risks through regulation (101). Analogizing to the international level, political contests between holders of climate-forcing and

climate-vulnerable assets may become more intense and politicized as stranding risk increases, shifting the focus of debate from distributional to existential and increasing the likelihood of uneven, national-level climate policy approaches with ramifications for free trade and investment (136). Border adjustment taxes, increasingly prominent as potential alternatives to international carbon pricing, may be able to dilute these incentives by limiting states' ability to free-ride on regulation implemented by other countries that results in asset stranding (137).

The green paradox holds that even credible climate policies can drive increased short-term consumption of high-carbon goods in anticipation of tighter regulation, raising future stranding risks by reducing the remaining carbon budget. However, endogenous growth modeling suggests this need not occur if high-carbon capital stocks are used to produce green goods and services. If this high-carbon activity also increases the productivity of all assets, more resources are available for green investment and green capital accumulates. Climate-compatible policies may therefore exist that can drive the required clean investment without stranding high-carbon capital unnecessarily (138). Anticipation of strong near-term climate policy can also mute the green paradox effect by accelerating divestment from firms holding affected assets in the period before the policy is implemented (139). Conversely, short-term green paradox effects can be greater when policies are less credible and carbon extraction markets more competitive. In oligopolistic or collusive markets (e.g., the Organization of the Petroleum Exporting Countries in oil markets), larger producers (particularly low-cost fossil fuel exporters concerned about peak demand) are able to sustain low prices in order to retain or expand their market share. This both accelerates high-carbon asset phaseout by preventing the entry of new firms in extraction markets and encourages a more rapid pivot to renewables among these excluded firms, while also curtailing asset stranding by allowing incumbents to operate their existing assets longer (140).

Equity. The prospect of asset stranding requires determining ethical principles (which may also be economically efficient) for how costs and benefits are allocated. This debate is increasingly couched in the terminology of just transition. The definition of a just transition remains largely contested, but in general refers to the protection of livelihoods disrupted by the shift to a sustainable economy and the equitable distribution of the benefits arising from it. The economic efficiency framing developed above, where stranding reflects costs to society rather than investors, partly addresses these issues by facilitating the design of policies that avoid unnecessary delay and support conversion to alternative fossil fuel sources at minimal social cost, but it does not address in great detail the distributional consequences for owners of assets and social groups affected by stranding.

Literature linking fairness with stranded assets beyond that already discussed is very limited, primarily focused on discourse and industry-labor bargaining, reserving little attention for developing economies. The discourse on fossil fuel divestment, for example, most often deploys stranded asset arguments to support the case for divestment as it appeals to enlightened developed-country investors, without considering how the ultimate benefits and costs of divestment are, or should be, distributed (141). Some initial analysis of coal phase-out policies in Europe suggests collaboration between industry and labor interests is associated with improved outcomes for affected workers by making the publication of transition, retraining, and redeployment plans a requirement for asset owners (130).

Supervisory Responses

As far as the authors are aware, as recently as 2012 there was no substantial ongoing work or dedicated specialist expertise in climate change or broader environmental issues at any major

Green paradox: the phenomenon in which anticipation of future climate policy creates incentives to maximize emissions in the short term

Just transition: the protection of livelihoods disrupted by the shift to sustainability and the equitable distribution of the benefits arising from it

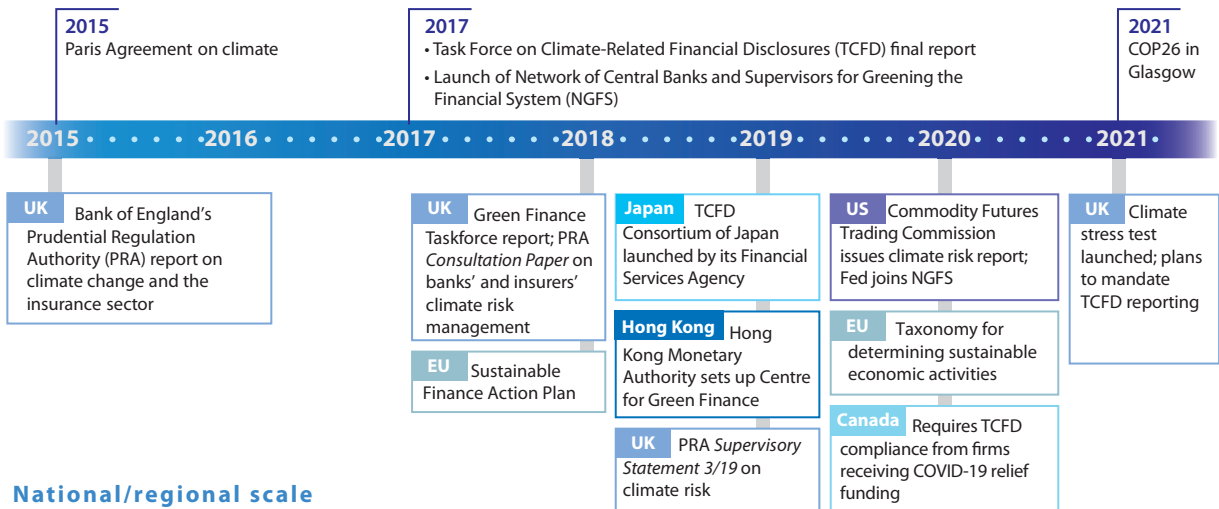
central bank. This includes the Bank of England (BoE), which is widely acknowledged as the first central bank to begin work on these issues in 2014. The BoE's seminal report (51), *Impact of Climate Change on the UK Insurance Sector*, was published on 29 September 2015, and the accompanying speech on the same day by then-BoE Governor, Mark Carney (60), constituted the first time a central bank called for consideration of climate-related risks and stranded assets in financial supervision. The report and speech also set out principles for how the BoE would approach climate change in the future and confirmed that it considered managing climate-related risk to be part of its statutory mandate.

The threat of climate and other environment-related risks stranding assets has since spurred work by many more financial supervisors and central banks who have announced, among other things, new supervisory expectations and climate stress tests to help improve the solvency of individual financial institutions, as part of what is known as microprudential supervision, as well as protecting and enhancing the resilience of the financial system as a whole, through policy measures that fall under macroprudential supervision (142). An important complement to work within central banks and supervisors has been the output of the TCFD, which was formed in 2015 and published a framework and set of recommendations in 2017 to help companies and financial institutions consistently measure, manage, and report their climate-related risk exposures (143).

Figure 3 presents a timeline of recent supervisory developments related to stranded assets.

Microprudential supervision. Various European central banks and supervisors, such as the Banque de France (BdF), the Dutch Central Bank (DNB), and the BoE, have been building up the required internal capabilities to incorporate environment-related risks into their microprudential supervision, i.e., their supervision of the solvency of individual financial institutions. In the United Kingdom, for instance, the BoE's Prudential Regulation Authority (PRA) has published detailed supervisory expectations for how firms should approach the climate-related financial risks

Global scale



National/regional scale

Figure 3

Timeline mapping the integration of climate change and climate risk into financial regulation and supervision in major jurisdictions and globally: Key events since 2015. Abbreviations: COP26, 26th United Nations Climate Change Conference of the Parties; COVID-19, coronavirus disease 2019; EU, European Union.

of four key areas: governance, risk management, scenario analysis, and disclosure (144). The Supervisory Statement published by the PRA in 2019, in which these expectations are laid out, has had strong signaling effects to financial markets and enhances the accountability of supervised institutions. Similar supervisory statements have been published by the European Central Bank (145), the Monetary Authority of Singapore (MAS) (146), and the Australian Prudential Regulation Authority (147), among others.

One key way in which supervisors have started to expect supervisee firms to integrate climate-related risks is through governance. That is, they expect financial institutions to have structures in place whereby climate-related risks are actively managed by senior management and boards. For example, in the United Kingdom supervised firms were required to assign individuals responsible for climate risk under the Senior Managers Regime by October 15, 2019. Similar expectations have been set by Brazil's Central Bank (148), the Central Bank of Malaysia, MAS, Banca d'Italia, Banco de España, and the Dubai Financial Services Authority (59).

Another key pillar for supervisors has been ensuring financial institutions have adequate risk management procedures in place to analyze climate-related risk. For instance, firms may be expected to use scenario analysis or stress testing to gauge short- and long-term financial risks. Supervisors can also require banks to incorporate climate risk into their internal risk management and governance frameworks, such as the Internal Capital Adequacy Assessment Process.

Scenario analysis can be used to explore the resilience and vulnerabilities of a firm's business model to a range of outcomes. The PRA, for instance, expects "approaches to scenario analysis to evolve and mature over time" (144, p. 14). Various central banks under the umbrella of the NGFS are currently developing climate stress tests with a different scope of granularity and time horizons. The BoE will use its climate stress test, the 2021 Biennial Exploratory Scenario, to explore the financial risk posed by climate change in a bottom-up approach that tests the resilience of current business models of the most important financial institutions (149).

Such stress tests will be key in informing central banks and their understanding of the resilience of individual financial institutions and the wider financial system. If climate stress tests find that climate-related risks are material, systemic capital buffers could be applied to mitigate the impact of climate-related risks (150). In practice, the main focus of central banks and financial supervisors at this stage is to help financial actors familiarize themselves with scenario analysis and facilitate such measures in internal risk management (151).

Where the potential impacts of environment-related risks are assessed to be material (for example, as a result of scenario analysis), supervisors may expect or require firms to demonstrate how they will mitigate these financial risks. Furthermore, in addition to voluntary disclosure it is increasingly accepted that mandatory disclosure should be implemented to strengthen and systematize the integration of climate-related risks (151). The recommendations of the TCFD are increasingly viewed as the best mode through which to disclose climate-related risks (152) and some jurisdictions, including the United Kingdom and New Zealand, have recently announced that disclosing under the TCFD will be mandatory (153, 154). As the NGFS noted in its first comprehensive report, "authorities can set out their expectations when it comes to financial firms' transparency on climate-related issues" (142, p. 27). Supervisors in France have already implemented mandatory disclosure in an attempt to systematize disclosure and to allow for transparent and consistent risk assessment by requiring financial and nonfinancial firms to disclose the climate-related risks they are exposed to under Article 173 of the French Law on Energy Transition for Green Growth. In the European context, this could be achieved by a review of the Non-Financial Disclosure Directive to make disclosure mandatory. And the Technical Expert Group on sustainable finance, set up by the EU Commission, seeks to provide guidance on how to improve corporate disclosure of climate-related risks (155).

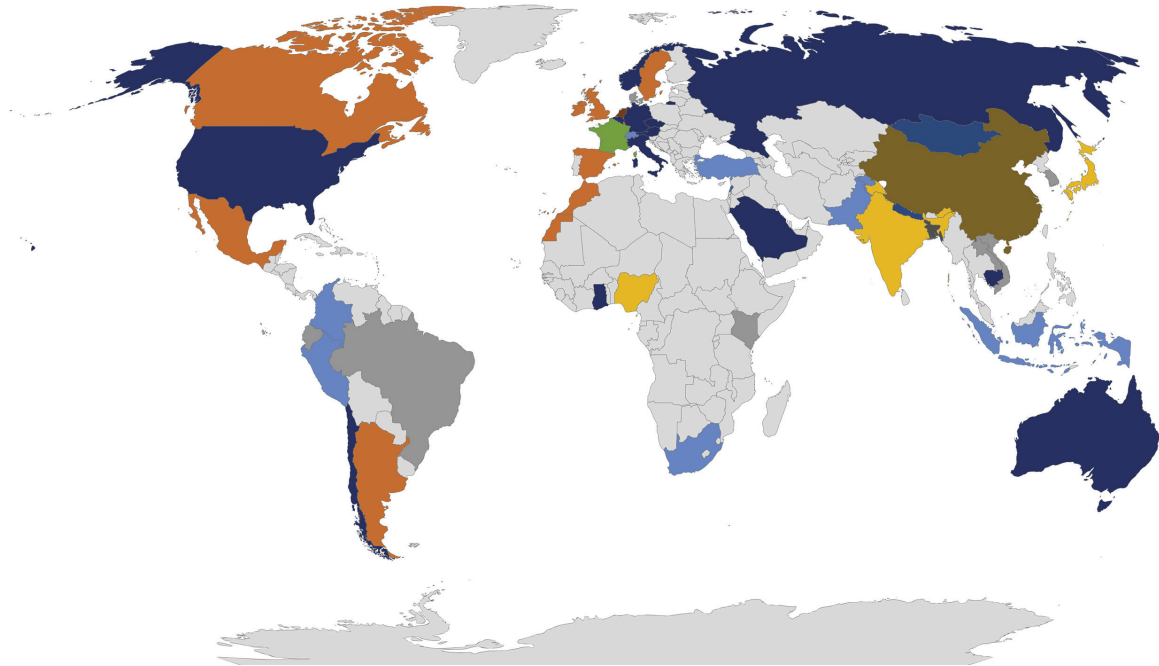
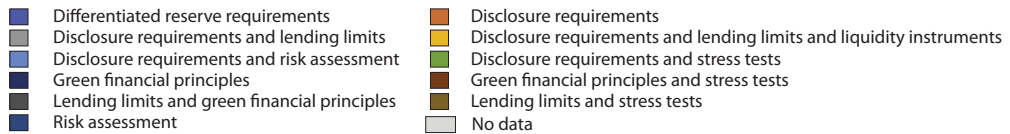


Figure 4

Geographical diffusion of country-level climate- and sustainability-related prudential measures (policies imposed by central banks on financial institutions to ensure soundness and stability). Includes policies on reserves, disclosure, principles for the definition of green finance, liquidity instruments, lending limits, and stress testing. Figure adapted with permission from Reference 159.

In general, developments in climate-related prudential policies vary substantially across developing and developed countries due to the different mandate scope of relevant institutions and systematic differences in the use of prudential tools (156) (**Figure 4**). For example, commercial banks and nonbank institutions in Bangladesh are required to allocate 5% of their total loan portfolio to green sectors (157). Countries such as China and Lebanon have established differentiated reserve requirements in proportion to local banks' green lending portfolio. At the height of its steel overcapacity crisis in 2002, China's government segregated nonperforming assets into dedicated entities to be wound down. This approach, since adopted by German utility RWE, may be an option for supervisors willing and able to use public "bad banks" to digest devalued assets (158). Banco do Brasil applied sectoral credit policies and issued a series of industry-specific and thematic green banking regulations to canalize and prioritize investment to certain sectors.

Macroprudential supervision. Although microprudential supervision concerns the financial health and soundness of individual institutions, macroprudential supervision concerns the stability of the financial system as a whole, and central banks and supervisors have come to appreciate that climate- and environment-related risks can potentially have a significant systemic effect.

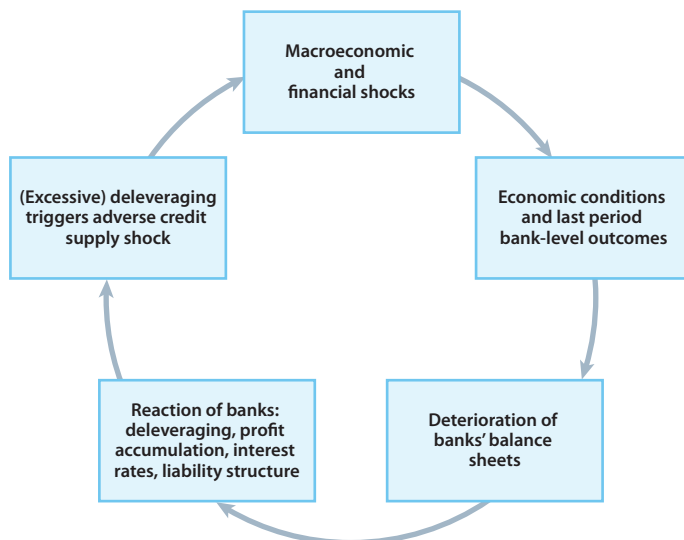


Figure 5

Stylized depiction of a feedback loop between the macroeconomy and financial institutions resulting from climate-related financial risks. Economic conditions, bank balance sheets, banks' responses, and credit market effects can interact and reinforce each other, leading to worse effects. Figure adapted with permission from Reference 161.

In scenarios where climate-related risks impact loan quality in carbon-intensive sectors (transition risks) or across all sectors (physical risks), numerous banks can incur a financial loss either at once or in close succession. This may trigger amplification effects within the banking sector and broader financial system, driving up interest rates between banks and slowing economic activity, which was experienced in the 2007–2008 Global Financial Crisis (160). Recent evidence from the European Systemic Risk Board (159) highlights the potential impact of climate-related financial risks on the banking system's resilience, noting the feedback loops of how these risks may materialize (see **Figure 5**). For example, a bank that is impacted by climate-related risks may reduce lending as a response. However, if the banking sector as a whole follows this strategy, there may be a credit supply shock. To mitigate the potential impacts of environmental-related risk, macroprudential supervisors have begun integrating these risks into their toolkit.

The following are examples of how environmental-related risk can be integrated into macroprudential supervision and current areas of active exploration by central banks and supervisors.

Climate stress tests. A climate stress test involves integrating climate scenarios into a macroprudential stress testing framework and understanding how financial institutions are impacted throughout the financial system, in addition to other macroeconomic impacts. For example, Battiston et al. (162) conducted a climate stress test of the financial system and found that climate policy timing matters. An early and stable policy framework would allow for smooth asset value adjustments and lead to potential net winners and losers. In contrast, a late and abrupt policy framework could have adverse systemic consequences. This is consistent with Thomä & Chenet (163), who conclude there may be a case for policy intervention to address the market failures and associated potential mispricing of risk, from the results of stress tests. Increasing awareness of associated stranded asset risks is also prompting calls for central bank asset purchases under

quantitative easing programs to adjust for these risks by underweighting sectors subject to greater potential stranding (164).

The DNB, BdF, BoE, and European Central Bank are currently developing such climate stress tests with different scopes (e.g., degree of granularity, distinct climate and policy scenarios, different time horizon, modeling feedback loops). Such stress tests will be key in informing central banks and their regulatory and policy ability about the resilience of individual financial institutions and the wider financial system.

Carbon countercyclical capital buffer. A carbon countercyclical capital buffer would require financial institutions to build up a capital buffer, i.e., a higher capital base, during periods of carbon-intensive credit growth at the aggregate level (165). This mechanism could support financial stability in two ways: first, by limiting banks' carbon-intensive credit exposures in the upswing of the carbon-intensive credit cycle—i.e., acting as a “speed limit”—and, second, by building buffers ex ante to absorb shocks to carbon-intensive loans (e.g., due to the materialization of stranded asset risks) (165).

Large exposure limits. When applied to climate change considerations, such a measure could limit a bank's overexposed position in carbon-intensive assets that are at a high risk of stranding due to the materialization of climate-related risks. For example, this could safeguard financial institutions in the face of catastrophic losses induced by physical climate risks and limit the losses that would be incurred from a sudden default of single counterparties with substantial values.

Similar objectives are reached with sectoral or asset-specific lending limits. This measure could be changed to limit an overleveraged position to a targeted group of assets—in this case carbon-intensive assets. The focus here lies not on the size of a single exposure, but rather focuses on the nature of the exposure. This could be justified if empirical evidence becomes available that suggests that various types of assets are inherently associated with a higher risk stemming from climate change (e.g., asset is related to a production facility in a highly vulnerable hurricane area or coastal sea area that is at high risk of flooding).

In contrast to lending limits, some central banks, when managing their own portfolio, have introduced more radical measures that include rejecting issuers with a large climate footprint in the case of the Swedish central bank (166), or the BdF and the DNB who have adopted a Responsible Investment Charter for the management of own funds.

International cooperation. The NGFS has set up five workstreams on microprudential supervision, macrofinancial issues, scaling up green finance, bridging the data gaps, and research. As part of these workstreams, the NGFS has published various reports that advance the understanding of the financial risk from climate change and has set out broad recommendations that are then accompanied by more specific research.

In the macroprudential realm, the NGFS suggests integrating climate-related risks into financial stability monitoring and assessing systemic risk in the financial system, by (a) mapping physical and transition risk transmission channels within the financial system and adopting key risk indicators to monitor these risks and (b) conducting quantitative climate-related risk analysis to size the risks across the financial system, using a consistent and comparable set of data-driven scenarios encompassing a range of different plausible future states of the world.

For the latter, the NGFS published a guide to climate scenario analysis for central banks and supervisors that encourages these institutions to build up in-house capacity and to improve their understanding around scenario analysis collaboratively (167). In this regard, central banks and supervisors are expected to develop methodologies and tools that allow the integration

of sector-specific scenario analysis into macroprudential stress tests. For instance, portfolios exposed to the power sector might be tested against scenarios with declining capacity factors and restrictions on high-carbon capital stock additions (168). Given the forward-looking nature of the risks and the inherent uncertainty associated with climate-related and environmental risks, such tools are necessary to adequately capture systemic risk. The NGFS also encourages relevant parties to offer technical assistance to raise awareness and build capacity in emerging and developing economies.

Climate-related transition risks:

caused by societal responses to tackling climate change and moving to a net-zero emissions economy, through policies, regulations, litigation, social norms, and technology

CONCLUSION

There has been a recent explosion in the quantity and quality of research on stranded assets caused by climate change and broader environment-related factors. Although much of the pre-2015 research focused on stranded assets caused by climate-related transition risks, including the idea of unburnable carbon, we have seen a rapid increase in work focused on other causes, particularly physical climate-related risks, biodiversity loss, and litigation. This trend looks set to continue given the scale of these risks and the inherent difficulties associated with measuring and managing them.

Research is also beginning to explore in much more detail the distributional implications of asset stranding and the resulting political economy frictions. Understanding how stranded assets will affect workers and communities, as well as the owners of assets and the governments dependent on them for tax revenue, is a prerequisite for realizing a just transition.

Since the BoE became the first central bank to call for the consideration of climate-related risks and stranded assets in supervision, central banks and supervisors across the world have accelerated their work on this topic, with significant implications for both microprudential and macroprudential supervision. This is changing behaviors across financial institutions and is ultimately affecting how the real economy accesses finance and investment and at what cost. This will redirect capital flows and itself will be a driver of asset stranding, as at-risk assets find it harder to secure capital.

Although this review has attempted to cover some parts of the latest literature since 2015, there is much that has not been included due to space constraints. There are other drivers of asset stranding being actively researched today, including societal and technological tipping points, work that seeks to understand how asset stranding will impact sector after sector of the global economy, and what this means for our societies and what we should do about it. We are confident that stranded assets research will continue to be extended successfully to new areas. This is essential if we are to continue to better understand and then integrate both the risk of and manifestation of stranded assets into real-world decision-making.

SUMMARY POINTS

1. Stranded assets can be caused by a wide variety of factors and are a feature of the creative destruction seen in economic systems. A significant amount of recent attention has focused on how environment-related factors, particularly those related to the climate crisis, could strand assets across different sectors and geographies and what this could mean for economies, companies, financial institutions, communities, and workers.
2. Even if emissions mitigation efforts succeed, stranded assets are likely to arise as a consequence of physical climate impacts and ecological degradation with widely varying impacts on different sectors.

3. Improving physical climate risk analysis to be able to better inform decision-making across the financial system requires more and better data, disclosure, analysis, and projections for climate hazards, exposures, and vulnerabilities.
4. Liability risks have the potential to act as both a driver and a consequence of the physical impacts of climate change and of the transition to a net-zero economy. Liability risks result from (a) mismanaging, (b) misreporting, or (c) causing climate change.
5. Litigation can lead to many outcomes giving rise to stranded assets: fines or penalties, class action damages, legal costs, changes in valuation, changes in credit ratings, reputational damage, market exclusions, direct regulation, asset confiscation, and restriction of insurance. It can also have other, more indirect internal costs for firms, such as management distraction and staff morale.
6. Moving beyond climate risks, there is growing concern among central banks, regulators, and financial market participants about the stranded asset risks associated with a loss of biodiversity and ecosystem services.
7. Research is beginning to explore in much more detail the distributional implications of asset stranding and the resulting political economy frictions. Understanding how stranded assets will affect workers and communities, as well as the owners of assets and the governments dependent on them for tax revenue, is a prerequisite for realizing a just transition.
8. Since the Bank of England became the first central bank to call for the consideration of climate-related risks and stranded assets in supervision, central banks and supervisors across the world have accelerated their work on this topic, with significant implications for both microprudential and macroprudential supervision. This is changing behaviors across financial institutions and is ultimately affecting how the real economy accesses finance and investment and at what cost. This will redirect capital flows and itself will be a driver of asset stranding, as at-risk assets find it harder to secure capital.

FUTURE ISSUES

1. What are the societal and technological tipping points that can create stranded assets?
2. How will asset stranding impact different sectors of the global economy?
3. How should the costs of stranded assets be borne, who will be impacted, and how can this be managed fairly?
4. What are the implications of stranded assets on corporate strategy?
5. How can we reform the financial system to minimize and manage stranded assets?
6. To what extent should adaptive investments be undertaken to prevent or reduce asset stranding due to the physical impacts of climate change?

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