Beijer Institute
OF ECOLOGICAL ECONOMICS

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

DISCUSSION PAPER

Finance, climate and ecosystems: a literature review of domino-effects between the financial system, climate change and the biosphere

Beijer Discussion Paper Series No. 278

Sanchez-García. P.A., V. Galaz, J. Rocha. 2022.

Beijer Institute of Ecological Economics
The Royal Swedish Academy of Sciences

Lilla Frescativägen 4A
Stockholm

+46 8 673 95 00
beijer@beijer.kva.se

www.beijer.kva.se

Finance, climate and ecosystems:
a literature review of domino-effects between the financial system, climate change and the biosphere

Beijer Discussion Paper No. 278

Paula Andrea Sanchez-García[1,2], Victor Galaz[1,3], Juan Rocha[1,4,5]

1. Stockholm Resilience Centre, Stockholm University, SWEDEN
2. Leibniz-Centre for Agricultural Landscape Research, GERMANY
3. Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, SWEDEN
4. South American Institute for Resilience and Sustainability Studies, Maldonado, URUGUAY
5. Future Earth, Stockholm, SWEDEN

Abstract

Climate change and biodiversity loss represent a potential threat to financial stability by increasing and creating novel forms of poorly understood market, credit, liability and operational risks. Until now there is no overview of the main mechanisms, methodologies, and impacts of such finance-related risks. This paper presents a systematic synthesis of 75 publications, and offer a detailed overview of this growing body of literature. We develop a typology of cascading effects across climate-ecology-finance, and identify possible gaps in current understandings of global change induced financial risks. Our review shows that there is a growing interest in climate related risks in the literature, yet their connections to ecological change is systematically underdeveloped. While an increasing number of methods have been developed in the last years, such as IAMs, scenario-based analyses, and network-based stress testing, there is little consensus and standardization on methods and practices for risk evaluation and reporting, and a lack of data availability for conducting climate change and other nature-related finance risks analyses. Most models continue to oversimplify the financial system and its linkage to the economy and the biosphere, despite growing efforts to address system connections and complex systems behavior. Early economic estimates in the literature indicate that climate change and biodiversity and ecosystems' loss are costly, together compromising 4-15% of the global GDP. Our findings also show that existing research is skewed towards European and USA-based financial institutions, thus risk and impact analysis on other countries and large economies such as India, China and Brazil are unstudied.

Key words: climate change, ecosystem loss, finance risks, cascading effects, systemic risks

INTRODUCTION

Anthropogenic perturbations have led to a warmer world with a diminished ice cover, changed precipitation patterns, and a heavily altered biosphere dominated by human modified landscapes (Steffen et al. 2011). The transgression of the Earth's climate and biosphere integrity creates a substantial risk of destabilizing the biophysical conditions in which modern societies have evolved (Rockström et al. 2009, Steffen et al. 2015). It is estimated that the cost of ecosystem services loss is about \$4.3 to \$20.2 trillion US dollars annually (1997-2011) (Costanza et al. 2014), with an estimated GDP reduction of 1.0 to 3.3% by 2060 due to global rising temperatures (ECB 2020a).

Climate change and biodiversity loss also represent a potential threat to financial stability by increasing and creating novel forms of poorly understood market, credit, liability and operational risks (Bolton et al. 2020, UN PRI 2020). For example, it is estimated that a transgression of the 2°C target of the Paris Agreement could lead to 20 times more economic losses due to the increase in intensity and frequency of extreme weather events, potentially costing up to \$14 trillion US dollar annually by 2100 (Caldecott et al. 2021). Droughts are also expected to cause significant economic losses. In the EU and the UK, drought losses are estimated to increase to nearly 45 billion Euros annually by 2100 under a 3°C warming scenario (EIOPA 2021a).

Financial institutions such as banks, asset managers, pension funds, and multilateral banks play a key role in the global economy by financing economic activities which alter the climate system and the biosphere (Crona et al. 2021). Examples include key biomes for the Earth's stability such as the Boreal and Amazon forests (Galaz et al. 2018), and marine systems (Jouffray et al. 2019). The strategies to curb, mitigate and adapt to climate change and ecosystems degradations are also expected to create financial risks and opportunities by inducing policy, technological, and behavioral changes with potential impacts on the economy (EIOPA 2021b). Transitioning to a greener economy is top priority to meet the Paris Agreement 2°C target. Yet, the transition might result in certain assets becoming stranded, i.e. suffering an unanticipated or premature downward, write-offs or revaluations due to disruptive innovations or policies of environmental nature (FSB 2020, NGFS 2020).

There is a growing need to understand how transitioning to a greener economy not only creates direct risks to the financial system through such stranded assets (e.g. loss of property value due to sea level rise), but also indirect and at times non-linear effects that unfold as the loss of resilience impacts various parts of the Earth system (Crona et al. 2021, Battiston et al. 2021). Climate and other environmental-related risks are however highly uncertain due to inherent domino effects between climate and ecosystems (Rocha et al. 2018), and their additional connections to the financial sector (Bolton et al. 2020, Kedward et al. 2020, Crona et al. 2021). They also raise several ethical concerns such as issues of inter- and intra-generational justice (Stern 2007).

The literature about risks to the financial sector created by climate change and other planetary changes like biodiversity loss, is growing rapidly. Such assessments often use different approaches, focus areas, models and data sources to analyze these complex risks. There is a growing need to compile the research on this topic to help build common ground among researchers and practitioners on how to assess these financial risks. Yet, to the best of our knowledge, until now there is no overview of the main mechanisms, methodologies, and impacts of these climate and environmental finance-related risks. Here, we a) make such a synthesis, and offer a detailed overview of this growing body of literature; b) develop a typology of these cascading effects across climate-ecology-finance; and c) identify possible gaps in current understandings of global change induced financial risks.

To be more precise, we ask: 1) How do climate and ecosystem change translate into financial risks? 2) What are the main methodological approaches to assess domino-effects between climate, ecosystems and the financial sector? 3) What are the most prominent economic and financial impacts of climate and ecosystems change?

METHODS

Searching criteria

We conducted a systematic literature review to identify the mechanisms of climate change and ecosystem loss-related financial risks (see Fig 1 for search terms). Searches were carried out in June 2021 with an update search in December 2021 on Scopus, resulting in 399 potential climate and biodiversity loss relevant publications. An additional search was carried out in the preprints *Econstore* and *RePec* to include relevant but potentially not yet published articles, leading to 9 additional publications. This search was complemented with a hand searching of grey reports in web pages of selected institutions (SI Table 1) between November and December 2021. The selected institutions represent key financial organizations and international partnerships from all around the world with a known interest in financial risks created by climate change and other environmental changes (primarily biodiversity loss). All relevant reports, working papers and occasional papers in English published between 2021-2015 were included in the analysis, except for assessments that are only available as online interactive platforms. We selected this five-year period to capture the growing interest in climate and environmental-related risks after the Paris Agreement in 2015. We also identified 120 additional climate and nature-related risk relevant publications in the grey literature. We selected 31 reports of these based on the type of institution, and the number of publications per institution category to get as diverse a set of reports as possible. We classified the consulted central financial institutions in eight different categories: multilateral financial institutions, central Bank, non-profit think tank, international non-governmental organization, academic institution, financial regulator, multilateral forum for policymakers. Based on the institutions categories, we created a balanced sub sample (N=31) of documents that were further codified (SI Table 2).

Inclusion criteria and data analysis

Based on the publications' abstract and titles, we first included all unique documents whose aim was to examine, describe or measure the impacts, effects and (or) risks of climate change, and (or) environmental degradation on the financial system (n=87). These impacts and effects could be direct or indirect, on risk of climate change, on risk on environmental degradation, or on risk on the financial system and its institutions. After a full-text reading, we only included studies that had at least the description or measurement of one real or expected risk, effect or impact of climate change or ecosystem degradation on the financial sector. The selection process resulted in a total of 75 relevant documents (SI Figure 1).

We used NVIVO for conducting a text analysis to identify 1) the mechanisms of climate change and ecosystem degradation-related financial risks; 2) the methods used to measure domino-effects; 3) the required data for analysis, and 4) the quantification of the impacts, scenarios, and projections (SI Table 3). Each paper was appraised in detail by one author and overseen and repeated independently by another. Disagreements in coding where solved after joint discussions. We classified publications based on the type of research conducted – empirical, synthesis and conceptual[1] – and the type of publication. Figure 1 below offers a detailed description of the selection process and methodology.

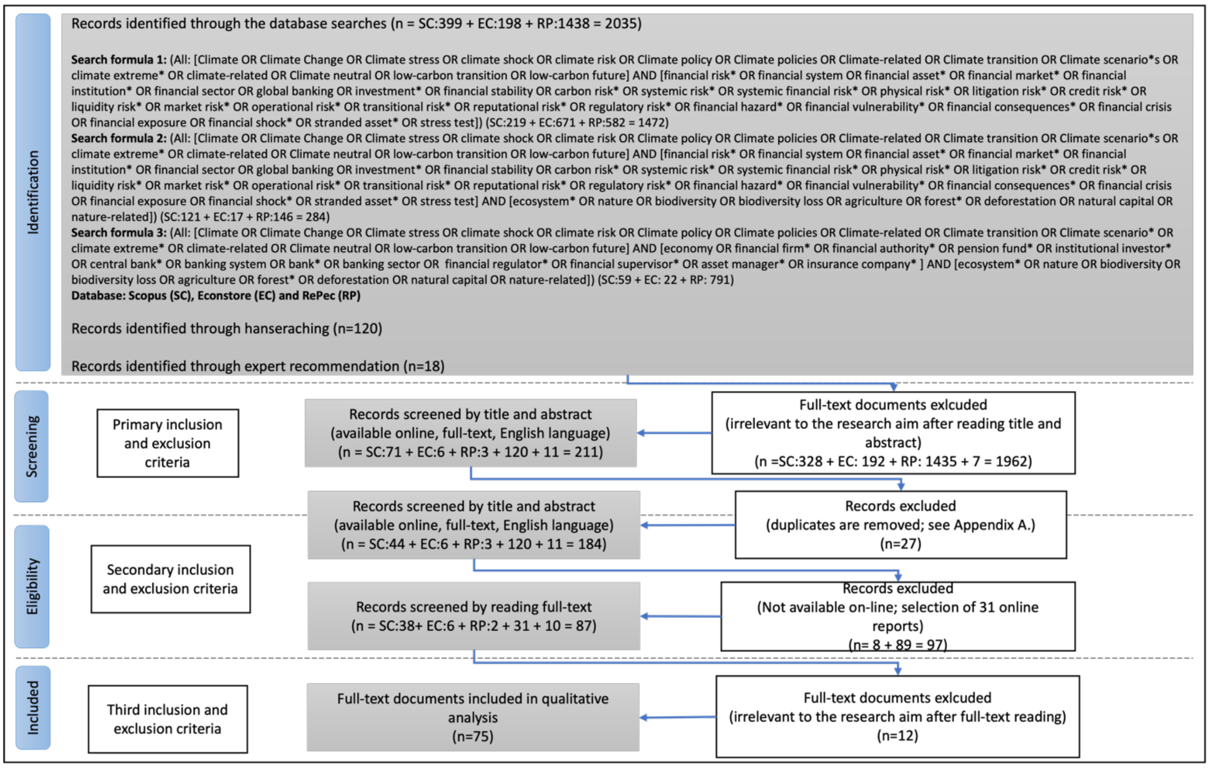


Figure 1. Detailed description of the literature review procedure.

[1] 'empirical' refers to work based on original data collection; 'synthesis' refers to work based on a compilation of existing data; and 'conceptual' refers to work that is primarily conceptual and/or opinion

RESULTS

Academic publications examining climate change and ecosystem and biodiversity loss related financial risks have increased in recent years (2015-2022), with the maximum number of publications in 2020 (SI Figure 2). Most of the publications based their findings on empirical evidence (n=22 out of 75 for academic literature; n=12/75 for grey literature), and less conducted a synthesis (n=12 for academic literature; n=13 for grey literature) or conceptual analysis (n=12 for academic literature; n=4 for grey literature) (SI Figure 3). We identified 62 (n=37 for academic literature; n=25 for grey literature) and 46 (n=28 for academic literature; n=16 for grey literature) publications addressing the spatial and temporal dimensions of climate and (or) nature-related financial risks, with 48 (n=23 for academic literature; n=25 for grey literature) out of 75 publications quantifying the expected impacts in economic terms (SI Table 4).

Most publications address climate change related risks (n=42 for academic literature; n=28 for grey literature) followed by publications describing nature (n=6 for academic literature; n=9 for grey literature) and ecosystems' loss (n=3 for academic literature; n=12 for grey literature) related risks (SI Table 5). Financial risks are mostly expected to be negative (n=40 for academic literature; n=31 for grey reports), with 36 (n=17 for academic literature; n=19 for grey literature) out of 75 publications recognizing the uncertainty and complexity of the effect of climate change and natural degradation on the financial systems, and only 8 publications expecting no impact of climate change, ecosystems' loss, or natural degradation on the financial system (n=6 for academic literature; n=2 for grey literature) (SI Table 5).

Most publications described climate change, ecosystems' loss, and natural degradation related risks at the global and regional scales, yet impacts are expected to occur both in the short and long-term (SI Figure 4.A and 4.B). Our selected publications mostly describe impacts affecting all the financial sector, asset managers and investors, banks, insurers, and firms; while impacts on central banks, pension funds and governments were less mentioned (SI Figure 4.C).

66 (n=37 academic literature; n=29 grey literature) out of 75 articles described a method to assess climate change or nature-related risks, with approximately two thirds reflecting on limitations (n=31 academic literature; n=20 grey literature) and advantages (n=30 academic literature; n=12 for grey literature) of the described methods (SI Figure 4.D). We found 12 (n=2 academic literature; n=10 grey literature) publications mentioning a methodological consensus on how to assess climate change and other related financial risks, yet 43 (n=20 for academic literature; n=23 for grey literature) out of 75 report data availability raise the need to conduct further analysis. Only 21 (n=9 for academic literature; n=12 for grey literature) publications described the type of data requirements for developing such additional analysis.

In the following sections, we present the findings linked to our three research questions. The first section describes how climate and ecosystem change are translated into financial risks, providing a detailed description of the risk transmission channel of transitional and systemic risks. Section two summarizes the advantages and limitations of the most relevant methodological approaches to assess domino-effects between climate, ecosystems and the financial sector. Section three describes the most prominent economic and financial impacts of climate and ecosystems change related financial risks. Lastly, we highlight knowledge gaps within the field of study and describe how system and resilience thinking can contribute to future research.

Climate change, ecosystem loss, and nature-related financial risks channels

Climate change and other environmental-related risks are mostly classified into physical and transitional risk (Figure 2) (Bernardini et al. 2021, Battiston et al. 2021), yet experts agree that both are expected to have an impact on the likelihood and magnitude of other financial-related risks such as market and credit, insurance, operational, and liability risks (ECB 2020b, Ansari and Holz 2020). These impacts can occur directly, through for example lower corporate profitability or the devaluation of assets; or indirectly, through macro-financial changes (ECB 2020b). Climate change and other environmental-related risks can further affect the resilience of business and financial institutions stemming liability risk and reputational loss (ECB 2020b)

Physical risks are the projected hazards that climate change and other environmental-related risks might have on the economy due to climate change, loss of ecosystem services, and environmental degradation (ECB 2020a, Bernardini et al. 2021, Battiston et al. 2021). Climate change and ecosystem degradation are viewed as having both direct and immediate negative impacts by increasing the frequency and intensity of extreme events such as hurricanes, floods or landslides; or chronic when arising from progressive shifts gradually increasing in temperatures and sea level (ECB 2020b). An increase of extreme weather events due to climate change can lead to the destruction of physical capital and households, business, and government, and as a result reduce the value of assets and profits and increase firms' operational risks. It can also increase public and private debt, and further increase markets and credit risks for financial institutions in the short-term (Bernardini et al. 2021).

Agriculture, forestry, fisheries, human health, energy, mining, transport and infrastructure, and tourism are sectors that are expected to be the most affected by physical risks (ECB 2020b). Increasing needs for compensation after climate-related shocks in high-risk areas such as coastal cities, could also transfer climate change related risks to the insurance industry (Bernardini et al. 2021). Environmental disasters might also be an indirect source of risk for financial intermediaries, disrupting not only businesses and households' activities but reducing the value of the assets provided as collateral for credit lines (Bernardini et al. 2021).

Transitional risks

Transitional risks are defined as the effects that the transitions to a low-carbon and greener economy might have on the economy and on the financial system (ECB 2020b). Transitional risks are more difficult to assess compared to direct risks because of the divergent effects that they might have on different sectors (Bernardini et al. 2021, Battiston et al. 2021, Diluiso et al. 2021). A low-carbon transition could, for example, have direct negative impact on fossil-fuel intense sector such as energy production, transportation, agriculture, and manufacturing by increasing these firms' cost of operation, and through reputational risks (ECB 2020b, Bernardini et al. 2021, Benz et al. 2021). A reduction of fossil-fuel use might also deepen the overall impact for the economy by increasing the cost of production of many goods and services due to a rise in energy prices (Bernardini et al. 2021). Technological innovations, change in consumers consumption behavior and policies created to facilitate a transition to a low-carbon or greener economy could also lead to unanticipated and premature losses of economic value (Ansari and Holz 2020, Benz et al. 2021, Cunha et al. 2021, Battiston et al. 2021). This could affect the value of the firms' financial contracts and portfolios exposed to those firms, such as equity and bond holdings of pension funds and bank loans (Ansari and Holz 2020, Battiston et al. 2021).

Stranded assets, meaning assets suffering from premature or unanticipated write-offs or downward revaluations due to a transition to a low-carbon or greener economy (Caldecott et al. 2013), are estimated to result in significant wealth loss globally, with a disproportionately larger loss on countries in the Global South and government agencies (see the Scenarios, projections and quantification of the impacts section). The former due to these countries' dependence on fossil-fuel dependent extractive industries (Ansari and Holz 2020). The latter is explained by government agencies holding the largest share of carbon-intensive portfolio values (49.45%), while other of investors (e.g., banks, pension funds, insurers) have a relatively low carbon risk exposure, averaging between 15.27% and 24.34% (Benz et al. 2021).

The overall positive or negative impact on the financial system through transitional risks will be heavily dependent on the velocity and size/importance of the impacted sectors in the economy, and on investors' ability to anticipate the impact of the introduction of climate policies and technological innovations (Bernardini et al. 2021, Battiston et al. 2021, Diluiso et al. 2021). Recent evidence suggests that there is a trade-off between physical and transitional risks. That is, as climate change and other environmental shocks impact on the economic and financial systems, the likelihood and intensity of physical risks will grow (FSB 2020, Commodity Futures Trading Commission 2020). A rapid transition to a low-carbon economy also increases other forms of transitional risks, while reducing the physical hazard of climate change and environmental degradation on the economy (ECB 2020b).

Systemic risks

The analyzed publications also distinguish between sector or firm-specific, and systemic financial risks. The first are described as the impacts that firms or sectors are exposed to due to physical and transitional risks. The latter is linked to the cumulative, non-linear and cascading effects that are expected to affect the whole financial system, with the risk of triggering financial crises (Bernardini et al. 2021, Battiston et al. 2021). Such systemic risks are recognized by authors as complex, non-linear and in many cases as radically uncertain, which make them harder to assess (Battiston et al. 2021). Increased financial interconnectedness, circularity across central financial institutions, high leverage and mispricing of assets is a key aspect of such systemic risks (Battiston et al. 2021). Proposed methods to evaluate systemic financial risks include integrated assessment models (IAMs), social networks analysis, scenario analysis and qualitative risk assessment (see Battiston et al. 2021). The evaluation and prevention of systemic risks is often viewed in the literature as the responsibility of banks and other financial authorities, yet it is also evident that the reduction of systemic risks will require the engagement of governments and other civil societal groups. Lack of transparency and open data hampers any attempt to quantify such risks. Figure 2 offers a summary of the identified domino-effects and risks in the literature.

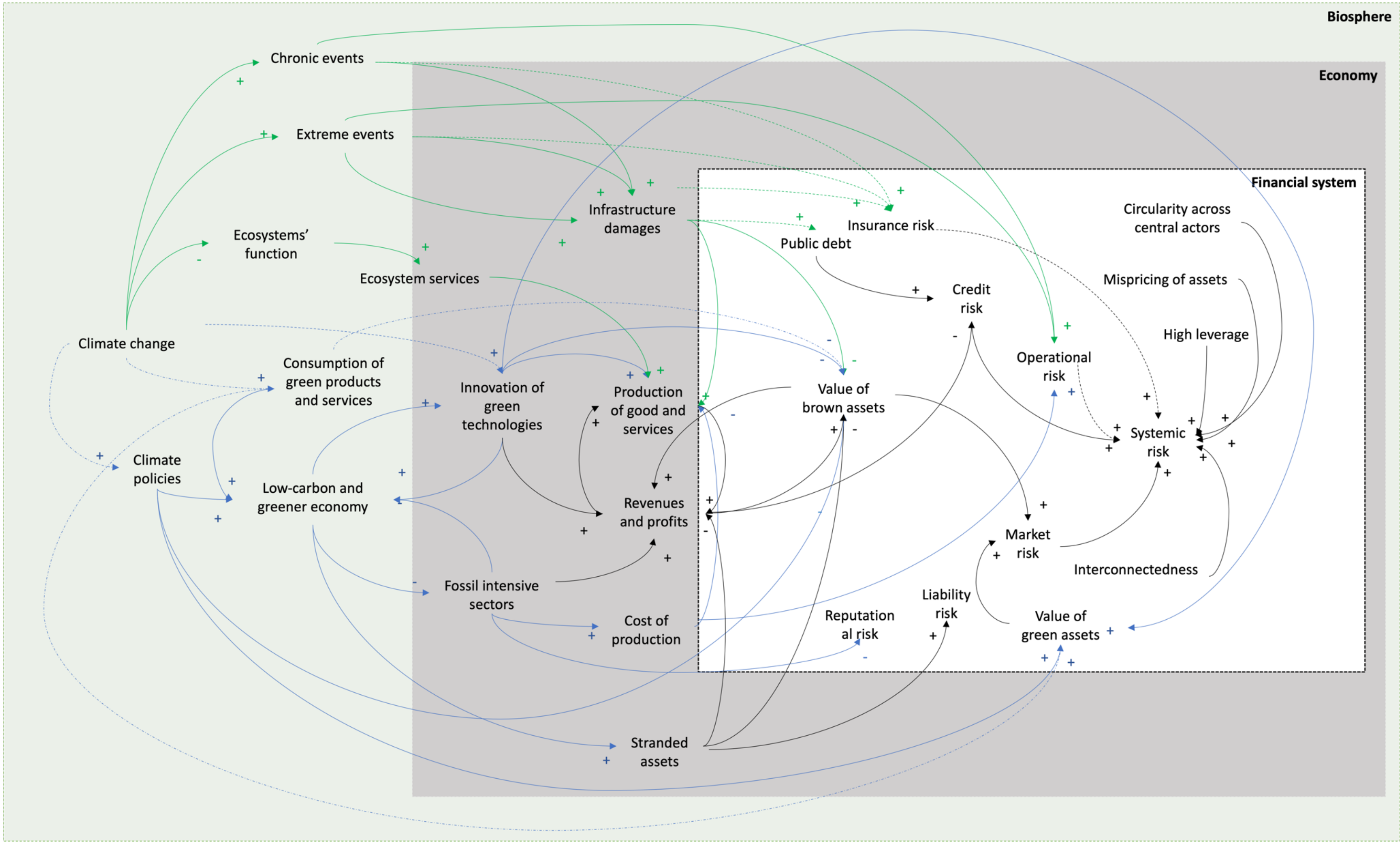


Figure 2. Transmission channels of physical (green), transitional (blue) and systemic climate and ecosystems' loss related financial risks.

Frameworks, methodologies and methods for assessing climate and other nature-related financial risks

Here we provide a general description of the most relevant frameworks, methodologies and methods to assess climate and environmental change related financial risks. We provide a general overview of how these methods are conducted and reflect on their advantages and limitations.

Integrated assessment models

Most of the financial and economic assessments of climate-related risks have adopted a cost-benefit approach. It compares the current costs of reducing future physical and transitional risks, with the benefits of avoiding future climate change induced damages (Campiglio et al. 2018, ECB 2020a, Keppo et al. 2021). The main analytical tool used to assess these climate-driven damages are Integrated Assessment Models or IAMs (ECB 2020a). IAMs are used to compare a range of possible pathways to achieve long-term policy goals, and simultaneously understanding the feedbacks and trade-offs between choices about the environment, the economy and energy sector (Keppo et al. 2021).

IAMs differs greatly in the way they define the complexity of climatic and economic variables, the spatial scales (e.g., global, regional, national) at which impacts are disaggregated and how the modelling is done (see Table 1 for a summary) (ECB 2020a, Keppo et al. 2021, In et al. 2022). IAMs also differ in the way they estimate climate and other nature related risks and impacts, with some trying to maximize welfare or minimize costs over time, and others simulating projected trends and dependencies in historical time series (Keppo et al. 2021). Yet, they generally include the analysis of the 1) projections of future greenhouse emissions under different scenarios over long periods of time (typically to 2050 or 2100); 2) the average temperature changes that result from increasing atmospheric carbon concentrations; 3) the average temperature change and other climatic effects linked to an increasing atmospheric carbon concentration; 4) the damage or loss functions that determines the economic impact of rising temperatures (generally expressed in lost GDP and consumption); 5) the cost of reducing greenhouse emissions in the present and the future, and 6) a detailed characterization of the economic dynamics, usually represented in a Computable General Equilibrium (CGE) model (ECB 2020a, Keppo et al. 2021).

Although IAMs are generally not meant to be normative nor provide a plan for policy makers due to their analytical limitations (linked to long-time horizon analysis and simplifications) – (Keppo et al. 2021), they have been criticized for not including the financial system as component of the economic model, neglecting actor heterogeneity, and assuming a quick return to steady state following a climate shock (Campiglio et al. 2018, Bolton et al. 2020, Keppo et al. 2021). In regards to transitional risks, IAMs have been criticized for their assumptions of a relatively smooth transition to a low-carbon economy, the general use of economy-wide carbon prices as a proxy for climate policies, and for overlooking key social and political forces influencing the transition (Campiglio et al. 2018, Bolton et al. 2020). Scholars have stressed that the neoclassical approach of most IAMs models limits the possibility of capturing the complex forces driving climate change, and thus their limited abilities in addressing the deep uncertainty linked to non-linearities in physical and transitional risks (Bolton et al. 2020). IAMs outcomes should this be interpreted cautiously by financial practitioners, regulators and supervisors (Bolton et al. 2020).

Table 1 Summary of some of the most relevant IAMs (UNCC 2022)

IAM name	General description
AIM	The Asia Pacific Integrated Model (AIM) is made up of three modules to measure the greenhouse emissions, climate change and climate change impact. The AIM model covers the Asia-Pacific region and is useful to analyze the development and diffusion of new technologies in the region.
ASF	The ASF model is a tool used to develop scenarios of future emissions based on different demographic, economic and technological assumptions. It is a useful model to evaluate land-use impacts of response measures due to their conceptualization of the linkage between biofuels, land use, technological development and GHG policy at a global scale.
E3ME	The model provides a framework for assessing energy-environmental-economy issues and policies in the EU, Norway and Switzerland. Thus, it is a useful tool to assess the socio-economic impact of climate change mitigation policies
E3MG	This IAMs is a sectoral econometric model useful to analyze long-term energy and environmental interactions and short-term effect of climate policy at the global scale. It has been described to be particularly useful to evaluate climate mitigations policies linked to taxes and subsidies.
ENTICE-BR	It is a dynamic growth model that conceptualizes economic activity, carbon emissions and the climate. It is mostly used to assess strategies to improve energy efficiency, development and diffusion of new technologies at a global scale.
ENV-Linkages	ENV-Linkages is the successor of the OECD GREEN model aiming to assist governments of the OECD countries in identifying least-cost policies linked to climate change mitigation, phasing out fossil fuel subsidies and other related growth policies.
FAIR	The model is relevant to assess the socio-economic impact of climate change mitigation policies in 26 world regions, 27 EU Member States, 224 UN countries.
FUND	This IAM is a build-up to study the role of international capital transfers in climate policy, being useful to analyze the social and economic cost of climate change transitioning strategies between countries and socio-economic groups at a global scale.

G-CUBED GINFORS	This is a multi-country, multi-sector equilibrium model used to study the impact of multiple environmental regulations, tax reforms, monetary policy and international trade, known for discriminating between financial and physical capital. It is useful to analyze the socio-economic impact of climate change mitigation and monetary policies.
GEM-CCGT	General equilibrium model created to evaluate the multilateral agreements on climate change and trade at the global level.
GEM-E3	This model provides relevant information on the interactions of the macro-economy, the energy system and the environment. GEM-E3 is used to simulate the effects of market-based instruments designed to drive the green energy and environmental transitions, evaluate the European Commision programs used to promote sustainable economic growth, and the implications of public finance and stabilize policies on trade, growth and behaviour of economic agents.
GEMINI-E3	Specifically designed to evaluate world climate policies at the macro and microeconomic levels, including taxation and trading.
GINFORS	This is a economy-energy-environment model with global coverage and a detailed disaggregation per sector. Due to its joint treatment of the environment, energy demand and the economy, the model is useful to assess the impacts of climate change mitigation policies on trade and long-term energy supply and demand in all EU and OECD countries and their trade partners.
GTEM	The GTEM is a dynamic multi regional and sectoral model representing the world economy. It is used to assess carbon sinks, clean development mechanisms and the international emissions trading for understanding the socio-economic impacts of climate change mitigation policies.
ICLIPS	The model provides an integrated assessment of climate protection strategies to support decision makers in their understanding of the socio-economic consequences of climate change mitigation policies and economic diversification methods at the global and regional level.
IMACLIM	This is a general equilibrium model designed to assess the macroeconomic price and quantity-based impacts of a carbon policy, being useful to evaluate the effects of changes in tax regimens and emission trading at the global level.
IMAGE	IMAGE is a multi-disciplinary and integrated system of models created to emulate the dynamics of the interactions of the global society, biosphere and atmosphere. Its strength is the assessment of the socio-economic impacts of policies that aim to reduce the land-use change related to greenhouse emissions.
MDM-E3	This is the most detailed econometric model linking the economy, the energy system and the environment in the UK. MDM-E3 is designed to analyze and forecast the changes in the economic structure, energy demand and environmental

	emission, being well-suited to assess the economic impacts of climate change mitigation policies in the country.
MERGE	The MERGE model was designed to estimate the global and regional impacts of greenhouse emission reduction. The model's strength is its flexibility to explore alternative views ranging from cost of abatement, damages from climate change, valuation and discounting, among others in Europe.
MERLIN	MERLIN is a cost-benefit model system used to determine the economic cost and benefits of air pollution control and climate change mitigation policies in Europe.
GCAM	This is an IAM focusing on the world's energy and agriculture systems. The model is mostly used to estimate the impacts of greenhouse emission related technologies and policies at a national and global scale, evaluate different technologies (e.g, carbon sequestration), model land-use and climate change.
MS-MRT	The MS-MRT is a computable general equilibrium model designed to evaluate the impacts of climate change mitigation policies on trade and the economy. This model is useful to evaluate the climate change policies on sectoral and trade-related impacts at a global scale.
NEMESIS	The model is a multi-country, macro-sectoral econometric model used to assess structural policies linked to the environment, air pollution, technology and economy in the EU countries.
PACE	Flexible system of general equilibrium models, integrating the economy, the energy system and the environment. The model is mostly useful to assess the long-term socio.economic effects of environmental policy, focusing on shifts in taxation and energy efficiency in 12 world regions.
PANTA-RHEI	This model assesses the link between the economy, the energy system and atmospheric emissions of the German economy, being helpful to analyze the energy-efficient policies and tax and subsidy schemes at the country level.
REMIND	This is a numerical model designed to assess the future of the world economy focusing on the development of the energy sector based on a set of population, technology, policy and climate constraints.
SGM	SGM is a computable general equilibrium model focusing on demographics, resources, agriculture, energy supply, household consumption and government expenditure. The model is suitable to evaluate the impacts of climate mitigation policies and technological innovations on projected energy consumptions and emissions.
TIAM	Comprising several thousand technologies in all sectors of the energy system, the model assesses the potential technological solutions to reduce greenhouse emissions. TIAM is well-suited to investigate the development of new green energy technologies and evaluating the conditions for the adoption of such technologies.

Scenario based analysis

The growing recognition of the limitations of traditional approaches for assessing the macroeconomic and financial effects of climate change and climate policies (Battiston et al. 2021), has led scholars and other financial actors to develop alternative methods for financial risk evaluation such as scenario analysis (Hassani 2016). The Network for Greening the Financial System (NGFS) has recommended the use of scenario-based analysis for assessing the implications of climate-related financial risks, and provide a set of climate scenarios that investors, central banks and supervisors are encouraged to use in their climate financial risk assessments (NGFS 2020b, Bertram et al. 2021). Scenarios include Net Zero 2050, Below 2°C, Divergent Net Zero, Delayed Transition, Nationally Determined Contributions, and Current Policies as a means to cover the orderly, disorderly and hot house world dimensions of the NGFS scenario matrix (see Bertram et al. 2021). Although the NGFS scenarios were generated using three IAMs (GCAM, MESSAGEix-GLOBIOM and REMIND-MAgPIE), they combine a macro-economic, agriculture and land-use, energy, water and climate modules into a common numerical framework, enabling the analysis of the complex and non-linear dynamics in and between the components (Bertram et al. 2021).

Scenario analysis is a forward-looking approach used to assess potential climate-related risks and their interaction (ECB and ESRB 2021, FSOC 2021, In et al. 2022). Such scenario analysis can be used to explore the vulnerabilities of financial actors and firms to climate change and policies and technological developments (Caldecott et al. 2021, FSOC 2021). The results can be useful for central banks and authorities for evaluating the resilience of the whole financial system (Bolton et al. 2020, FSOC 2021). Yet, with the increasing number of scenarios proposed for evaluating climate-related financial risks, it is recommended to use scenario analysis only when the number of scenarios considered represents an acceptable variation of plausible futures or when the selected scenarios represent the extreme bounds of plausible futures (Chenet et al. 2021).

Stress tests

A climate stress test involves the integration of one or more climate scenarios into a macroprudential stress testing framework for understanding how climate-related extreme, rare or adverse shocks impact financial institutions through the financial system (Caldecott et al. 2021, Chenet et al. 2021). Stress tests are commonly conducted at the firm or systemic level (Chenet et al. 2021). At the firm level, stress tests can be used to translate macro-financial and sectoral scenarios into firm-specific shocks affecting the firm's balance sheets (ECB 2020a). Examples of existing parameter estimation using a firm-level approach are the probability of default, the so-called IFRS 9 transition probabilities, the loss given default, the revaluation of equity holdings, and the evaluation of corporate bonds– for a complete list of the methodological handbook see (ECB 2020a).

Network-based climate stress testing has been used for evaluating climate-related systemic risks, allowing practitioners to understand how externalities are spread and how they build up into systemic risks (Battiston and Martinez-Jaramillo 2018). Network models increasingly used to assess financial stability include: default contagion, distress contagion, common assets contagion and funding liquidity contagion (Battiston and Martinez-Jaramillo 2018).

Although stress tests are becoming an important tool for assessing climate-related risks, stress testing techniques lack adequate incorporation of solvency, liquidity and common assets into a coherent framework (Battiston and Martinez-Jaramillo 2018). Stress tests are an intensive data approach that require both the financial and economic data, which is often absent, too low a resolution or hard to access (Battiston and Martinez-Jaramillo 2018, Campiglio et al. 2018, Kedward et al. 2020) Stress tests only provide a static snapshot of financial risks, not accounting for the dynamic nature of the interaction between the macroeconomy, the finance system, climate change and policies (Campiglio et al. 2018). The lack of the temporal dimension of both scenario analysis and stress testing makes them unable to capture the complex system dynamics linked to ecological thresholds (Kedward et al. 2020). It has also been argued that stress tests might be better suited for assessing physical risk rather than transitional risk, because the latter is susceptible to unexpected drastic policy changes or rapid consumers' behavioral changes (IAIS 2018).

Ecosystem and Natural capital assessments

Some practitioners use the Environmental, Social and Governance (ESG) framework to measure the sustainability performance of firms, and as a method to assess climate and nature-related financial risks. ESG is a three-dimensional framework with an outside-in and inside-out perspective used to assess a firm's climate change mitigation, biodiversity protection, sustainable resource extraction and use, pollution prevention and control, and the sustainable use and protection of water and marine resources (IPSF 2021). By using an outside-in perspective, investors can use ESG data to aggregate and compare different environmental and social information at the company, fund or portfolio level and often compare it against different benchmarks (Abramskiehn et al. 2015). This type of impact and risk assessment has multiple ESG indexes with varying methodologies, component companies, geographic and sector emphases, and past performances, yet most indexes are new and many are managed by some of the largest mainstream index providers such as MSCI, STOXX, and State Street (Abramskiehn et al. 2015). ESG-metrics also have a number of weaknesses related to their inability to properly measure ecosystem change and Earth system interactions (Crona et al., 2021).

The assessments of environmental and nature-related financial risks of firms and other financial actors is also done through ecosystem services assessments. For instance, the Dutch Central Bank (DCB) used an ecosystem services approach to evaluate the dependency of Dutch financial institutions to natural capital. The DCB used the ENCORE database to examine the dependency of 86 business processes on 21 ecosystem services, showing that the highest dependency of Dutch financial institutions relies on ecosystem services providing groundwater and surface water (DNB 2020). Similarly, the Swiss Re Institute (SRI) developed the Biodiversity and Ecosystem Services (BES) index to assess the importance and health of multiple ecosystem services for every square kilometer at a global scale (see Retsa et al. 2020). SRI later used the ENCORE database to assess how far economic sectors depend on BES. By applying the SRI BES Index to relevant risks, insurance and reinsurance can zoom in to assess their risk exposure.

Scenarios, projections, and economic quantification of the impacts

Direct impacts and residual damages from physical climate-induced impacts are expected to cost about $2.5 trillion US dollars in a business-as-usual scenario (Caldecott et al. 2021), representing about 2 to 10% of the global GDP by 2050 (ECB 2020a) and up-until 20% of the global GDP by the 2100 (ECB and ESRB 2021). Under this scenario, it is estimated that losses from rising sea levels could cost more than $14 trillion US dollars annually (Caldecott et al. 2021), and a total of 13.8 trillion US dollars of financial assets could be destroyed (ESRB 2016). By mid-century, losses from increasing hurricanes are expected to rise up as much as 275% (Caldecott et al. 2021) and weather extremes in the transport sector may become responsible for a 0.5 to 1% global GDP reduction (ECB 2020a). Still, there is a great uncertainty regarding the cost of impacts at higher temperatures, with losses ranging from 0 to 12.5% of the global GDP for a temperature increase of 3.5°C (see ECB 2020a).

Curbing global warming could halve economic loss by 70% (ECB and ESRB 2021). Yet, transitioning to a low-carbon economy will require the decarbonization of at least 60% of the energy sector, causing a 2 to 5% reduction of the global GDP (ESRB 2016). Transitioning to a low carbon economy is estimated to cost 1 to 4 trillion US dollars with 50-80% of fossil fuels reserves becoming stranded assets (Löffler et al. 2019). Stranded assets could cost up to $20 trillion US dollars in a delayed transition scenario and 0.4% of global financial assets' value are at risk (Semieniuk et al. 2021). A stringent policy transition over the next twenty years is expected to lead to a loss of $28 trillion US dollars in revenues coming only from 15 oil, gas and coal companies (ESRB 2016).

Although most transitional risks are expected to grow over time, transitioning impacts are already causing important financial losses today. $20 billion dollars in capital expenditure from oil and gas projects were cancelled over 2015 (Cleveland et al. 2015). The (Carbon Tracker Initiative 2018) have also estimated that 42% of global coal plants are already unprofitable as of 2018, a percentage that is expected to grow up to 72% by 2040 due to falling renewable energy costs, carbon pricing, and air pollution regulations. Yet, transitional risks can be significantly reduced if the climate-related mitigation and transition strategies are pursued.

The degradation of natural capital is also expected to have costly consequences for the economies and the financial sector. For instance, land cover changes cost $2-20 trillion US dollars, and land degradation cost an additional $6-11 trillion US dollars per year, between 1997 and 2010 (Retsa et al. 2020); that is about 7.3% of global GDP (University of Cambridge Institute for Sustainability Leadership 2020). 29% of the global GDP has been estimated to be highly dependent on the biosphere, and an additional 26% assessed to be moderately dependent (Retsa et al. 2020).

Conservation and restoration of ecosystems could represent investment and business opportunities. For instance, the seafood industry could increase annual profits by $53 billion US dollars from investing $5 to 10 billion US dollars annually in biodiversity conservation (Retsa et al. 2020). Conservation of strategic ecosystems, e.g., coastal wetlands, could lower flood-damages by $52 billion US dollars annually (*ibid*). Transitioning to a low-carbon economy is expected to create business opportunities for investors and other financial actors. For example, renewable energy finance has grown from $45 billion in 2004 to $270 billion US dollars in 2014 (Osofsky et al. 2019). In 2018, renewable energy sources accounted for 55.3% of all the gigawatts of new power generation added, meaning an increase of renewable energy investments and deployment (*ibid*). The quantification of transitioning and conservation strategies is less explored and mostly limited to investments in renewable energy.

Climate and ecosystem change impacts will impact countries and regions in highly unequal ways (IPBES 2019, IPCC 2022). Developing economies are expected to be more vulnerable to rising temperatures (Batten 2018, Bolton et al. 2020, FSB 2020). Africa and the Asia Pacific are expected to be among the most affected by climate change, according to the ND-GAIN vulnerability index (FSB 2020). Transitioning to a low-carbon economy is also expected to have larger effects on fossil-fuel dependent economies disproportionately affecting Global South economies such Middle Eastern and Latin American countries (Batten 2018, FSB 2020, Ansari and Holz 2020). Although clean energy programs are also expected to alleviate poverty and provide opportunities for new industries in these economies, the magnitude of the positive impacts resulting from green technologies and innovation will depend on their institutional environment (Banga 2019, Ansari and Holz 2020).

Despite the fact that developing economies are expected to suffer the most from the transition to a low-carbon economy, they have been the least studied in terms of risk and low-carbon investment performance analyses (Ansari and Holz 2020, Cunha et al. 2021). Our results show that current knowledge about climate and other nature-related financial risks is concentrated to Europe and the USA (Table 2). In the USA, there is growing recognition that climate change will have a larger financial and economic impact on vulnerable populations such as communities of color, Native American communities, and other disadvantaged communities. South-eastern and southern regions in Europe are projected to have the highest numbers of severely affected sectors and domains, while the Arctic Circle is expected to be mostly affected by increasing air and sea temperatures, leading to greater economic losses in these areas (EIOPA 2021b).

Regarding transition risk, in Europe, financial actors are less exposed to climate policies affecting the fossil-fuel sector and more exposed to shocks to energy intensive sectors, with exposure ranging from 45.2% for Insurance and Pension Funds, to 47.7% for Government (Battiston et al. 2017). Under uncertain, delayed and sudden low-carbon transition, first and second round effects entail a systemic risk to the financial sector in Europe (*ibid*). Other studies show that in Europe has a significant low-carbon premium which became statistically significant since 2012 (Bernardini et al. 2021).

A number of studies have been conducted to assess climate and nature-related risks to the financial sectors of China, Mexico and Brazil. For example, it is estimated that a 1°C increase in average temperatures will lead to a fall of China's financial stability index by 0.048 in the long-term (Liu et al. 2021). Dunz et al. (2021) evaluated compound impact of COVID-19 and climate physical risks in Mexico and showed that procyclical lending and credit market constraints amplify initial shocks by limiting the recovery of firms, and undermining the effectiveness of higher government spending. Cunha et al. (2021) used a Carbon Efficient Index to assess Brazil's financial performance, and noted that investments in carbon-efficient companies contributed positively to portfolio performance, thus offering investors an opportunity to reduce climate risk exposure in stock markets. Table 2 summarizes existing economic estimates of climate and nature-related financial risks, and identifies some notable knowledge gaps.

Table 2. Publications mentioning, addressing the estimated impact, risk, effect of climate and other nature-related financial risks at different scales (e.g., economic loss in US, Euros, percentage of GDP loss, percentage of expected risk or impact increase), and their estimated economic loss in US million dollars (n=47 publications).

Scale of the impact	Number of publications	Estimated loss (USD, B= billion; T=trillion)
Global	28	
Physical risks	15	
Extreme and chronic weather events	8	300B – 43T

Loss of ecosystem services	3	19B – 20T
Transitional risks	8	
Stranded assets	6	200B – 18T
Green energy investments	2	150B – 1700B
Global North	26	
EU, Switzerland, and Norway	18	1.5B – 8T
USA	17	368T – 8T
UK	5	No estimates
Canada	4	No estimates
Australia	2	No estimates
Japan	1	No estimates
Global South	9	
China	4	No estimates
India	1	No estimates
Russia	2	No estimates
Latin America (Brazil, Mexico)	2	No estimates
Southeast Asia (Vietnam, Thailand, Philippines, Indonesia)	1	314B - 500B
Middle East countries	1	No estimates
Caribbean region	1	No estimates
Africa (South Africa)	1	No estimates

DISCUSSION

Although climate and ecosystem change related risks are increasingly recognized as a complex and uncertain threat to the financial system, our review shows that research has a strong emphasis on conceptualizing and assessing direct climate related risks. As a result, it is considerably less known to what extent domino-effects between climate, ecosystems and the financial sector pose systemic risks to financial stability. The reason why such knowledge gap has emerged could be a lack of global quantified targets on biodiversity that can be translated into goals for investor and other financial actors; a poor understanding of how ecosystem services and the economy interact; and a lack of standardized data, metrics and expert knowledge to evaluate corporate risk, performance and dependence linked to biodiversity and ecosystems' loss (DNB 2020, UN PRI 2020). Overcoming this gap will require quantitative and qualitative assessments of climate and ecosystem change related financial risks that are comparable across temporal and spatial scales.

Our synthesis shows that only a few studies assess both climate and ecosystem change related financial risks. There were no publications exploring the trade-offs and synergies between climate and other nature-related financial risks. Further research could benefit from studying how the interactions between climate change and loss of ecological functions amplify financial risk, as well as identifying the key financial actors with the agency to mitigate the such risks. It is clear that quantifications of such risks will prove important as a means to allow investors to better understand their overall performance, their management opportunities, and dependence on ecosystems and a resilient biosphere.

The increased number of frameworks, methods, and indexes that attempt to assess climate and other nature-related risks is notable. However, it is also clear that there is limited consensus, absence of systematic comparative efforts, and standardization of best practices for risk evaluation. Data availability for risk analysis is a pervasive problem, primarily because firms and financial actors do not report (nor make an effort to assess) their environmental footprints (Abramskiehn et al. 2015, ESRB 2016, Battiston et al. 2017, ECB 2020b, FSB 2020, Caldecott et al. 2021, ECB and ESRB 2021, Chenet et al. 2021). This is one of the main constraints for assessing such financial risks. Calls for action of central banks and financial authorities for requesting mandatory disclosure of this information are not uncommon (Abramskiehn et al. 2015, Caldecott et al. 2021, IPSF 2021).

Robust risk quantifications based on models of changes in the climate system and its interactions with the economic system, has in addition proven challenging (Bolton et al. 2020, Chenet et al. 2021). Simplified models can result in an underestimation of climate and other environmental risks.

Although this is true for all types of the analyzed nature-related risks, financial risks linked to biodiversity and ecosystems' loss represent an additional challenge due to the lack of clarity on how the biosphere and the economic system interact (Abdul Razak et al. 2020). Most of the biodiversity and ecosystems' loss related risk assessments are based on dependency of economic activities and sector on ecosystem services. However, the lack of agreement on which dependency criteria to use, makes it challenging to reach methodological consensus (Batten 2018, Retsa et al. 2020).

We identified that most of the climate change, ecosystems' loss, and nature-related risk assessments have been conducted for economies in the global North like the USA, the UK and Europe, with some additional publications addressing economic impacts in other large Asian and Latin American economies such as China and Brazil. Yet, less publications assess the impact of climate and other nature-related financial risks on economies in Latin America, Africa, and Asia, despite some of these areas being biodiversity hotspots and major biological carbon reservoirs. Including financial risk analysis on these areas is a key challenge due to their expected higher vulnerability to climate change and biodiversity loss-related financial risks.

CONCLUSIONS

There is a growing recognition that changes to the climate system and the biosphere pose intertwined, novel and unfolding risks to the financial system. Climate change and other nature-related risks are commonly classified into physical and transitional risks. Physical risks can be acute or chronic weather patterns such as increasing hurricanes, droughts, temperatures, while transitional risks result from the (un)expected effects of policies, technological innovations and changes in consumers' behavior aiming to mitigate climate and environmental changes. Complex and nonlinear interactions of physical and transitional risks and their effects on financial risks are likely to increase the likelihood and magnitude of market, credit, operational and liability risks, potentially compromising the economic and financial stability worldwide.

Understanding how interacting climate and ecosystems' risks affect the financial sector is becoming increasingly urgent. Our synthesis showed that although there is a growing interest in climate related risks, their connections to ecological change has been underdeveloped focusing mainly on transmission mechanisms from direct climate impacts to the finance sector. We argue that future research could explore other risk transmission pathways to better understand the connections between financial risk, climate change and ecosystem degradation. Thus, a more comprehensive, is key for investors and other financial actors to better understand their risk exposure and dependency to the Earth system as a whole.

Our review shows that there is a growing number of available methods to assess climate change and other nature-related financial risks. Yet, there is little consensus and standardization on methods and best practices for risk evaluation, comparison, and reporting. Lack of data availability and transparency emerged as one of the key barriers to improve risk assessment regardless of method. Most models also oversimplify the financial system and its linkage to the economy and the biosphere. Measuring the financial risks associated with biodiversity and ecosystems' loss has proven particularly challenging, and should be a priority for future research.

Funders

This report builds on research in the project *"Networks of Financial Rupture - how cascading changes in the climate and ecosystems could impact on the financial sector"* (2020-00198) funded by Formas. The Beijer Institute of Ecological Economics at the Royal Swedish Academy of Sciences has also contributed through the program "Complexity, Technology and Governance".

References

Abdul Razak, L., M. H. Ibrahim, and A. Ng. 2020. Which sustainability dimensions affect credit risk? Evidence from corporate and country-level measures. *Journal of Risk and Financial Management* 13(316).

Abramskiehn, D., D. Wang, and B. Buchner. 2015. *The landscape of climate exposure for investors*.

Ansari, D., and F. Holz. 2020. Between stranded assets and green transformation: Fossil-fuel-producing developing countries towards 2055. *World Development* 130(104947).

Banga, J. 2019. The green bond market: a potential source of climate finance for developing countries. *Journal of Sustainable Finance and Investment* 9(1):17–32.

Batten, S. 2018. *Climate change and the macro-economy: A critical review*.

Battiston, S., Y. Dafermos, and I. Monasterolo. 2021. Climate risks and financial stability. *Journal of Financial Stability* 54(100867).

Battiston, S., A. Mandel, I. Monasterolo, F. Schütze, and G. Visentin. 2017. A climate stress-test of the financial system. *Nature Climate Change* 7(4):283–288.

Battiston, S., and S. Martinez-Jaramillo. 2018. Financial networks and stress testing: Challenges and new research avenues for systemic risk analysis and financial stability implications. *Journal of Financial Stability* 35:6–16.

Benz, L., S. Paulus, J. Scherer, J. Syryca, and S. Trück. 2021. Investors' carbon risk exposure and their potential for shareholder engagement. *Business Strategy and the Environment* 30(1):282–301.

Bernardini, E., J. di Giampaolo, I. Faiella, and R. Poli. 2021. The impact of carbon risk on stock returns: Evidence from the European electric utilities. *Journal of Sustainable Finance and Investment* 11(1):1–26.

Bertram, C., J. Hilaire, E. Kriegler, T. Beck, D. N. Bresch, L. Clarke, R. Cui, J. Edmonds, M. Charles, A. Zhao, C. Kropf, I. Sauer, Q. Lejeune, P. Pfleiderer, J. Min, F. Piontek, J. Rogelj, C.-F. Schleussner, F. Sferra, B. van Ruijven, S. Yu, D. Holland, I. Liadze, I. Hurst, and van B. Ruijven. 2021. *NGFS Climate Scenarios Database: Technical documentation V2.2*.

Bolton, P., M. Despres, L. A. Pereira da Silva, R. Svartzman, and F. Samama. 2020. *The green swan: Central banking and financial stability in the age of climate change*.

Caldecott, B., A. Clark, K. Koskelo, E. Mulholland, and C. Hickey. 2021. Stranded Assets: Environmental drivers, societal challenges, and supervisory responses. *Annual Review of Environment and Resources* 46:417–447.

Caldecott, B., J. Tilbury, and Y. Ma. 2013. Stranded Down Under? Environment-related factors changing China's demand for coal and what this means for Australian coal assets, Smith Sch. *Enterp. Environ. Univ. Oxford*.

Campiglio, E., Y. Dafermos, P. Monnin, J. Ryan-Collins, G. Schotten, and M. Tanaka. 2018. Climate change challenges for central banks and financial regulators. *Nature Climate Change* 8(6):462–468.

Carbon Tracker Initiative. 2018, November 30. Powering Down Coal: Navigating the economic and financial risks in the last years of coal power. https://carbontransfer.wpengine.com/reports/coal-portal/.

Chenet, H., J. Ryan-Collins, and F. van Lerven. 2021. Finance, climate-change and radical uncertainty: Towards a precautionary approach to financial policy. *Ecological Economics* 183(106957).

Cleveland, S., R. Schuwerk, and C. Weber. 2015. *Carbon asset risk: From rhetorical to action*.

Commodity Futures Trading Commission. 2020. *Managing climate risk in the U.S. financial system: Report of climate-related market risk, subcommitee, market risk advisory committee of the U.S. commodity futures trading commission*.
Costanza, R., R. de Groot, P. Sutton, S. van der Ploeg, S. J. Anderson, I. Kubiszewski, S. Farber, and R. K. Turner. 2014. Changes in the global value of ecosystem services. *Global Environmental Change* 26(1):152–158.
Crona, B., C. Folke, and V. Galaz. 2021. The Anthropocene reality of financial risk. *One Earth* 4(5):618–628.
Cunha, F. A. F. de S., E. Meira, R. J. Orsato, M. C. Klotzle, and A. F. P. Lucena. 2021. Do low-carbon investments in emerging economies pay off? Evidence from the Brazilian stock market. *International Review of Financial Analysis* 74(101700).
Diluiso, F., B. Annicchiarico, M. Kalkuhl, and J. C. Minx. 2021. Climate actions and macro-financial stability: The role of central banks. *Journal of Environmental Economics and Management* 110(102548).
DNB. 2020. *Indebted to nature: Exploring biodiversity risks for the Dutch financial sector*.
Dunz, N., A. Hrast Essenfelder, A. Mazzocchetti, I. Monasterolo, and M. Raberto. 2021. Compounding COVID-19 and climate risks: The interplay of banks' lending and government's policy in the shock recovery. *Journal of Banking and Finance*.
ECB. 2020a. *Climate change and the macro economy*.
ECB. 2020b. *Guide on climate-related and environmental risks*.
ECB, and ESRB. 2021. *Climate-related risk and financial stability*.
EIOPA. 2021a. *Report on non-life underwriting and pricing in light of climate change*.
EIOPA. 2021b. *Methogological paper on potential inclusion of climate change in the Nat Cat standard formula*.
ESRB. 2016. *Too late, too sudden: Transition to a low-carbon economy and systemic risk*.
FSB. 2020. *The implications of climate change for financial stability*.
FSOC. 2021. *Report on climate-related financial risk*.
Galaz, V., B. Crona, A. Dauriach, B. Scholtens, and W. Steffen. 2018. Finance and the Earth system – Exploring the links between financial actors and non-linear changes in the climate system. *Global Environmental Change* 53(September):296–302.
IAIS. 2018. *Issues paper on climate change risks to the insurance sector*. Basel.
In, S. Y., J. P. Weyant, and B. Manav. 2022. Pricing climate-related risks of energy investments. *Renewable and Sustainable Energy Reviews* 154(111881).
IPBES. 2019. *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Bonn, Germany.
IPCC. 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Page (H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, v. Möller, and A. OkemB. Rama, editors). Cambridge University Press, Switzerland.
IPSF. 2021. *State and trends of ESG disclosure policy measures across IPSF jurisdictions, Brazil, and the US*.
Jouffray, J.-B., B. Crona, E. Wassénius, J. Bebbington, and B. Scholtens. 2019. Leverage points in the financial sector for seafood sustainability. *Sci. Adv* 5(11).
Kedward, K., J. Ryan-Collins, and H. Chenet. 2020. *Managing nature-related financial risks: A precautionary policy approach for central banks and financial supervisors*.
Keppo, I., I. Butnar, N. Bauer, M. Caspani, O. Edelenbosch, J. Emmerling, P. Fragkos, C. Guivarch, M. Harmsen, J. Lefevre, T. le Gallic, M. Leimbach, W. Mcdowall, J. F. Mercure, R. Schaeffer, E. Trutnevyte, and F. Wagner. 2021. Exploring the possibility

space: Taking stock of the diverse capabilities and gaps in integrated assessment models. *Environmental Research Letters* 16(053006).
Liu, Z., H. Sun, and S. Tang. 2021. Assessing the impacts of climate change to financial stability: Evidence from China. *International Journal of Climate Change Strategies and Management* 13(3):375–393.
Löffler, K., T. Burandt, K. Hainsch, and P. Y. Oei. 2019. Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem. *Energy Strategy Reviews* 26(10042).
NGFS. 2020a. *Overview of Environmental Risk Analysis by Financial Institutions*.
NGFS. 2020b. *NGFS climate scenarios for central banks and supervisors*.
Osofsky, H. M., J. Peel, B. Mcdonnell, A. Foerster, and W. Chair. 2019. Energy re-investment. *Indiana Law Journal* 94(2):595–652.
Retsa, A., O. Schelske, B. Wilke, G. Rutherford, and R. de Jong. 2020. *Biodiversity and ecosystem services: A business case for re/insurance*. Zurich.
Rocha, J.C., Peterson, G., Bodin, Ö, and Levin, S. 2018. Cascading regime shifts within and across scales. *Science* 362(6421):1379–1383.
Rockström, J., W. Steffen, K. Noone, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley. 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society* 14(2):32.
Semieniuk, G., E. Campiglio, J. F. Mercure, U. Volz, and N. R. Edwards. 2021, January 1. Low-carbon transition risks for finance. Wiley-Blackwell.
Steffen, W., A. Persson, L. Deutsch, J. Zalasiewicz, M. Williams, K. Richardson, C. Crumley, P. Crutzen, C. Folke, L. Gordon, M. Molina, V. Ramanathan, J. Rockström, M. Scheffer, H. J. Schellnhuber, and U. Svedin. 2011. The Anthropocene : From Global Change to Planetary Stewardship. *AMBIO* 40:739–761.
Steffen, W., K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers, and S. Sörlin. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223).
Stern, N. H. 2007. *The economics of climate change: the Stern Review*. Cambridge University Press.
UN PRI. 2020. *Investor action on biodiversity: Discussion paper*. London.
UNCC. 2022, May 17. Integrated assessment models (IAM). https://unfccc.int/topics/mitigation/workstreams/response-measures/integrated-assessment-models-iams-and-energy-environment-economy-e3-models#:~:text=Integrated%20assessment%20models%20(IAM)%20aim,earth%20systems%20and%20their%20interactions.
University of Cambridge Institute for Sustainability Leadership. 2020. *Biodiversity loss and land degradation: An overview of the financial materiality*.

Supplementary Information

Finance, climate and ecosystems:

a literature review of domino-effects between the financial system, climate change and the biosphere

TABLE CONTENT OF SUPPLEMENTARY TABLES

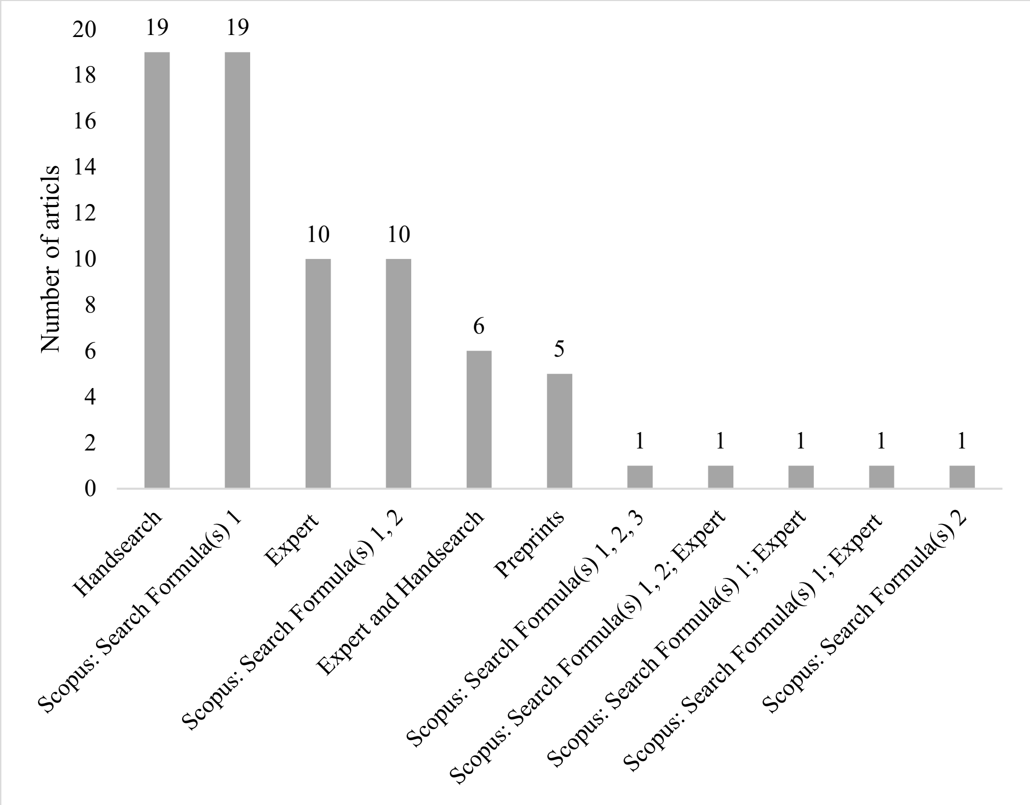
TABLE CONTENT OF SUPPLEMENTARY FIGURES

SI Table 1 List of consulted institutions for conducting handsearching (November and December 2021)

No.	Institution
1	Network for Greening the Financial System (NGFS)
2	Task Force on Climate-related and Disclosures (TFCD)
3	Financial Stability Board (FSB)
4	European Systemic Risk Board (ESRB)
5	European Central Bank (ECB)
6	Financial Stability Oversight Council (FSOC)
7	Subcommittee on Climate-Related Market Risk of the Market Risk Advisory Committee (MRAC)
8	International Platform for Sustainable Finance (IPSF)
9	Coalition of Finance Ministers for Climate (CAPE) (no relevant reports found)
10	International Association of Insurance Supervisors (IAIS)
11	Climate Finance Initiative (CFI)
12	Carbon Tracker Initiative (CTI)
13	World Economic Forum
14	UNEP Finance Initiative (UNEP-FI)
15	UNPRI
16	European Insurance and Occupational Pensions Authority (EIOPA)
17	Bank of England
18	Bank of Mexico
19	Dutch Central Bank
20	Banque de France (all in French)
21	International Monetary Fund
22	Industrial and Commercial Bank of China
23	Swiss Finance Institute
24	Sustainable Insurance Forum (SIF)

SI Table 2 Number of organizations, preliminary selected reports and final report selection based on organization type.

Type of organization	Organizations	Publications	Selected publication
Multilateral financial institutions	7	80	8
Central Bank	6	19	8
Non-profit think tank	2	8	4
International non-governmental organization	1	4	3
Academic institution	1	3	2
Financial regulator	4	5	5
Multilateral forum for policymarkers	2	1	1
Total	23	120	31



SI Figure 1 Number of articles obtained per unique combination of search formula and(or) criteria (n=77)

SI Table 3 Code notebook. First, second and third level codes used for text analysis of selected publications

First level	Second level	Third level	Code instructions
Domino-effect mechanism			Identify the described feedbacks, synergies, relationship that link effects, hazard, risk, etc. of climate change, biodiversity loss and other ecosystem impacts on the financial sector
	Type of domino effect		What is the type of domino-effect described by the authors? (if there is another common domino-effect create a new category)
		Climate Change (CC)	Climate Change □ Financial sector
		Ecosystems and biodiversity loss (BL)	Ecosystems degradations and (or) biodiversity loss □ Financial sector
		Climate Change and Biodiversity loss (CC and BL)	Climate Change and Biodiversity loss□ Financial sector
		Other	Other □ Financial sector
	Type of impact, effect or risk		What is the type of impact, effect or risk on the financial sector described by the authors?
		Positive	The domino-effect is expected to have an overall positive

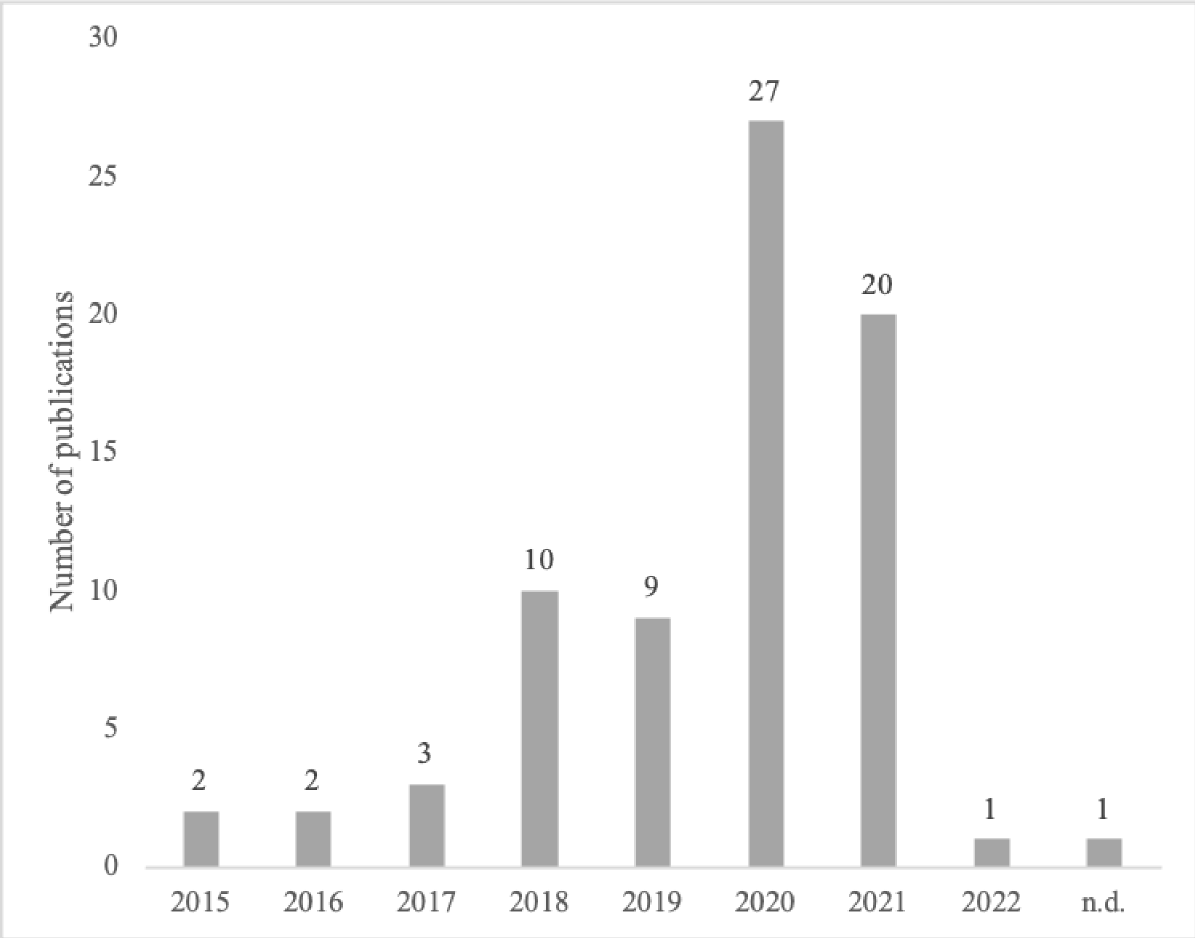
			impact/effect on the financial sector
		Negative	The domino-effect is expected to have an overall negative impact/effect on the financial sector
		Neutral	The domino-effect is expected to have no positive/negative impact/effect on the financial sector
		Uncertain/Unknown	There is no certainty regarding how the domino-effect(s) are expected to affect the financial sector
	Temporal scale		What is the temporal scale of the domino-effect described by the authors? Sub-categories will be determined inductively
		Short-term	The authors make clear thar the impact/effect described is expected to be observed in the long run (>11 years)
		Long-term	The authors make clear thar the impact/effect described is expected to be observed in the long run (<10 years)
	Spatial scale		What is the spatial scale of the domino-effect described by the authors?
		Global	The authors make clear that impact/effect/risk

			described is expected to be seen at a global level
		Regional	The impact/effect/risk described by the authors is expected to affect multiple/several countries with clear spatial boundaries (e.g., Global North, Global South, Europe, North America, Southeast Asia, etc.)
		National	The impact/effect/risk described by the authors is expected to be seen in at a country level (e.g., Germany, USA, Malaysia, etc.)
		Sub-national/Local	The impact/effect/risk described by the authors is expected to be seen in a region, state, location within a country
Financial actors			Within the financial sector, who is expected to be affected by the domino-effect described by the authors?
	Pension funds		
	Banks		
	Insurance sector/companies		

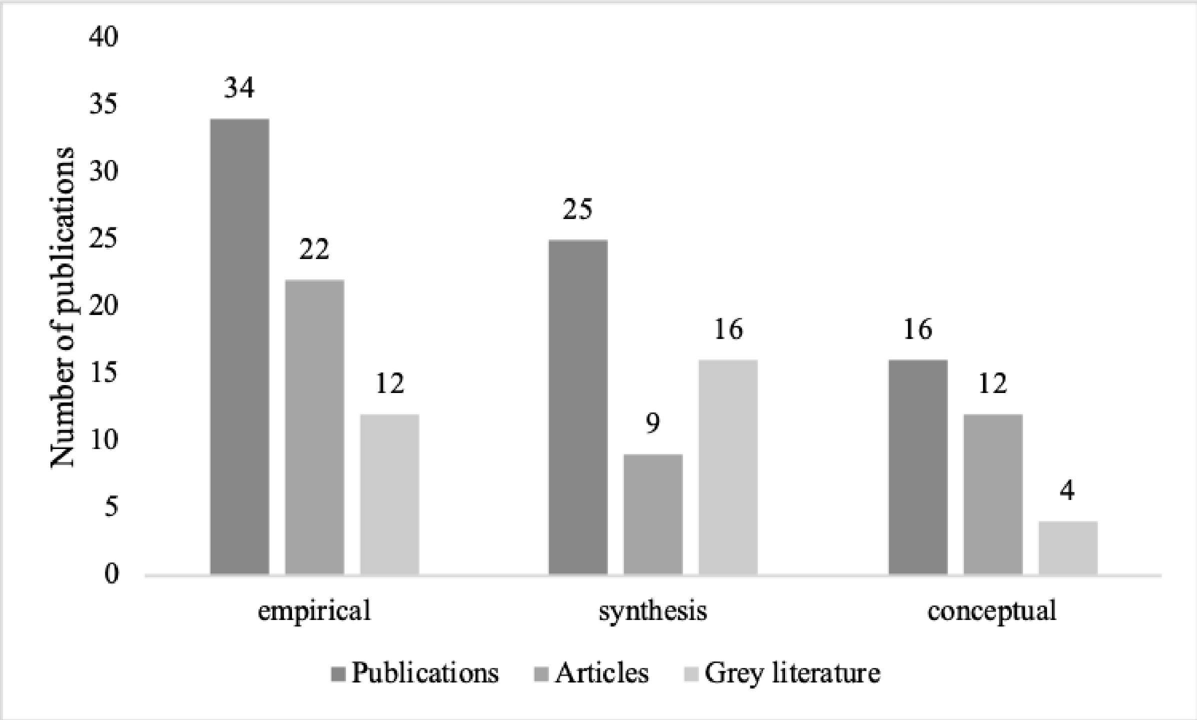
	Financial authorities, regulators, and/or supervisors		
	Asset managers and investors		
	All the financial sector		
	Governments		
	Firms		
	Other		
Methodologies used to assess domino-effect risks			
	Method(s)		What are the methods used/proposed to assess the risk/impact/effect(s)?
	Constrains and/or limitations of the method(s)		What are the constrains and/or limitations of the proposed method(s)? (if any)
	Pros and/or advantages of the method(s)		What are the advantages of the proposed method(s)? (if any)
	Methodological consensus		Does the article talk about consensus for using the described method(s)? and if so, how?
		Yes	The argues describes there is a

			methodological consensus
		No	The argues there is no methodological consensus
		Not mentioned	The article does not address this issue
Required data for analysis			
	Data type		Does the article mention data availability issues?
	Availability		Does the article mention the data type needed to develop further the analysis?
Projections/scenarios			
	Temporal scale		What is the temporal scale of the projections described by the authors? Sub-categories will be determined inductively
	Spatial scale		
		Global	The authors make clear that projections described are expected to be seen at a global level
		Regional	The projections described by the authors are expected to affect multiple/several countries with clear spatial boundaries (e.g., Global North, Global South,

			Europe, North America, Southeast Asia, etc.)
		National	The projections described by the authors is expected to be seen in at a country level (e.g., Germany, USA, Malaysia, etc.)
		Sub-national/Local	The impact/effect/risk described by the authors is expected to be seen in a region, state, location within a country
Quantification of the impact			Is there any quantification of the impact(s)? if so, how?
Knowledge gaps			What are the knowledge gaps in the field/methods described by the authors?



SI Figure 2 Number of published documents based on the year of publication (2015-2021) (n=75)



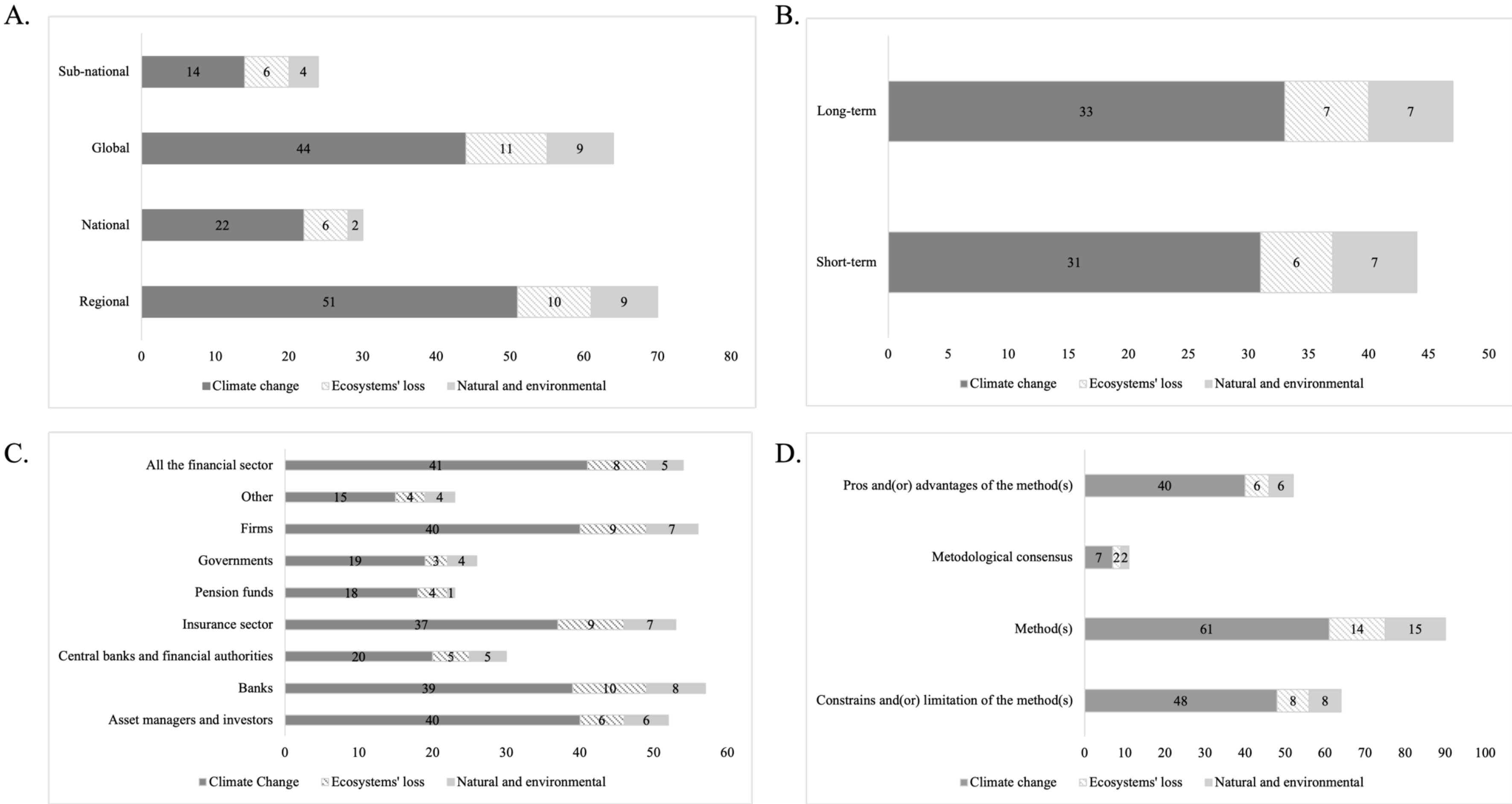
SI Figure 3 Number of published documents based on the type of research conducted defined as follows: 'empirical' refers to work based on original data collection; 'synthesis' refers to work based on a compilation of existing data; and 'conceptual' refers to work that is primarily conceptual and/or opinion (n=75)

SI Table 4 Number of publications describing the type of impact, the spatial and temporal dimensions and the quantification or projection of the financial risk

Domino-effects	Number of Publications	Articles	Grey literature	%
Type of impact, effect, or risk	75	43	32	100,0
Spatial scale	62	37	25	82,7
Temporal scale	46	28	16	61,3
Quantification of the impacts	48	23	25	64,0

SI Table 5 Number of publications describing the type of risk (climate change, natural environmental, ecosystems' loss) and risk (negative, positive, uncertain, neutral)

Type of risk/publication	**Negative**		**Positive**		**Uncertain**		**Neutral**		**Total**	
	Articles	**Grey literature**	**Articles**	**Grey literature**	**Articles**	**Grey literature**	**Articles**	**Grey literature**	**Articles**	**Grey literature**
Climate Change	39	27	21	18	17	17	6	2	48	28
Natural and environmental	2	9	2	7	2	4	0	0	6	9
Ecosystems' loss	5	12	0	7	2	6	0	1	3	19
Total	40	41	22	20	17	19	6	2	51	56



SI Figure 4 A. Number of publications describing impacts at the global, regional, national, or sub-national scales. **B.** Number of publications describing impacts with a short or long-term effect. **C.** Number of publications describing on different financial and economic actors D. Number of publications describing one or more methods for assessing climate change and other related financial risks, their limitations and (or) advantages, and the existence or not of a methodological consensus to assess such risks (n=75).