GeoJournal (2024) 89:213
https://doi.org/10.1007/s10708-024-11174-8

The geography of climate change risk analysis at central banks in Europe

Csaba Burger · Dariusz Wojcik

Accepted: 11 July 2024

Abstract The potentially limiting nature of central bank mandates, together with non-existent standards to assess the impact of climate risks used to inhibit the incorporation of climate change considerations in central bank decisions. This paper analyses how, despite these challenges, climate change risk analysis spread among central banks by examining 941 European financial stability reports of 38 central banks in Europe and their source references. We show that the Dutch and Belgian central banks pioneered significant engagement with climate change risk in financial stability reports, followed by central banks in other Eurozone countries. Then the ECB stepped in, aggregated novel research methods into an accepted analytical framework, and moved to the centre of the stage of the process. Our analysis indicates that various types of proximity played a significant role in the spread of climate friendly central bank mandate interpretations and analytical techniques, but the engagement of a central player was crucial.

Keywords Climate change · Central banks · Risk analysis · Economic geography · Financial geography · Financial innovation · Proximity · Sustainable finance · European Central Bank

C. Burger
MNB (Central Bank of Hungary), Krisztina krt. 55, 1013 Budapest, Hungary
e-mail: burgercs@mnb.hu

D. Wojcik (✉)
National University of Singapore, Singapore, Singapore
e-mail: dwojcik@nus.edu.sg

Introduction

There are significant differences in the way central bank mandates relate to climate change. Many Asian central banks seem open towards incorporating the fight against climate change in their policies. For example, the Reserve Bank of India (RBI) addressed environmental aspects in a note to its supervisees in 2007, followed by the Bangladesh Bank regulations making banks incorporate environmental dimensions in lending in 2011 (Durrani et al., 2020). In Europe, however, most central banks had initially been hesitant to consider climate change in their policies, given their missing or ambiguous legal mandates (Dikau & Volz, 2021). Parallels can be drawn with the asset management industry, where fiduciary duty, a legal obligation to consider only financially relevant factors in investment decisions, was interpreted as a need to focus on short-term returns (Clark & Hebb, 2005). Trustees started to incorporate longer term considerations such as climate change slowly and by imitating others (Woods, 2011).

The goal of this paper is to describe and account for the spatio-temporal process whereby central banks in Europe gradually started to engage with

Published online: 13 September 2024

climate change risks. We do so by using the sample of 941 financial stability reports (FSRs) of 38 central banks in Europe, published between 2003 and 2022. We identify and analyse bigrams, i.e. pairs of words related to climate change that appear in the FSRs, and we apply a graph-analysis to study source references of the FSRs. These methods allow us to tackle three questions. Where and when did the recognition of climate change risks by European central banks start? How did it spread across Europe in terms of time and space? How did the harmonization of analytical approaches play out in a geographical sense? Addressing these questions is important. First, it helps us understand the evolution of sustainable finance as a process of innovation, grounded in the context of particular times and spaces. Second, our study represents a contribution to financial geography, as it uncovers the spatial production of finance with regard to central banks' engagement with climate change risks.

We show that central bank mandate interpretations have started opening slowly towards climate change-related topics since the Paris Agreement of late 2015 (EP, 2018; MNB, 2022). This included the systematic measurement and tracking of climate risk exposures (BIS, 2021; EBA, 2022). Initially, however, the methodologies and data concerning climate risks were almost nonexistent, and their development required time-consuming research and data gathering. The discussion of climate risks in financial stability reports started in the Central Bank of the Netherlands (De Nederlandsche Bank, DNB) and the National Bank of Belgium (NBB). It subsequently spread across Europe, with various types of proximities playing a significant role in the diffusion process (Rutten, 2016; Simandan, 2016). Fairly quickly, however, the collection and publication of methodologies moved to the European Central Bank (ECB), which started coordinating the ways to measure the financial stability impact of climate change, and also began drafting Eurozone-wide analyses in a uniform manner. We expect that in the future, climate change related financial risk analysis may not only follow more similar methodologies across countries, but central banks may develop more or less harmonized macroprudential regulatory measures on the topic (ECB/ESRB, 2022).

This paper proceeds as follows. The next section discusses the literature on the geography of innovation in relation to climate change and central banks. Section 3 details our data and methods. The following sections present a three-part analysis of: the evolution of European central bank climate change risk considerations in FSR reports, the map of these considerations, and the networks of their source references. The last section concludes.

Climate change, central banks, and the geography of innovation

The 2008 global financial crisis made evident that central banks' narrow focus on monetary policy, complemented by a separate micro- and macroprudential regulation and supervision does not grant sufficient attention to financial stability risks (Balls et al., 2018). The subsequent widening of central banks' accountability created the public illusion that central banks are „*solely responsible for managing the economy, restoring full employment, ensuring strong growth, preserving price stability and safeguarding financial stability*" (Dall'Orto Mas et al., 2020: 23). Some central bank leaders, recognizing the long-term threat of climate change on financial stability, voiced their concerns on the tension between public pressure and the limiting nature of central bank mandates. In his famous speech at Lloyds, Mark Carney, who governed the Bank of Canada from 2008 to 2013, and the Bank of England from 2013 to 2020, stressed that the implications of climate change are *"beyond the business cycle, the political cycle, and the horizon of technocratic authorities, like central banks, who are bound by their mandates"* (Carney, 2015). As a result, both more relaxed mandate interpretations and new sustainability mandates were witnessed during the 2010s (e.g., MNB, 2022).

Initially, as Dikau and Volz (2021) showed, only a small minority (12%) of 135 central banks in their sample adopted explicit sustainability mandates, and majority did not even have implicit references to sustainability. Zooming in on Europe, Dikau and Volz (2021) showed that during the 2010s, most EU central bank mandates only indirectly referred to sustainability, by citing Article 3 of the Treaty on European Union. It states that the EU "[…] *shall work for the sustainable development of Europe based on balanced economic growth and price stability, a highly competitive social market economy, aiming at full employment and social progress, and a high level*

of protection and improvement of the quality of the environment".

According to both Dikau and Volz (2021) and Durrani et al. (2020) the growth in the adoption of climate change and sustainability in central bank mandates turned strong and evident after the Paris Agreement, signed on 12 December 2015 and entered into force on 4 November 2016. Its signatories agreed on country-level legally binding targets on CO_2 emissions. Subsequently, the European Parliament (EP) reaffirmed its implications for the European Central Bank in its 2016 annual report, stating that *"the ECB as an EU institution is bound by the Paris Agreement"* (EP, 2018). This moment was a clear signal for most EU members: as the second anniversary of the Paris Agreement in 2017 drew closer, the Network for Greening the Financial System (NGFS) was created by eight central banks (French, German, Dutch, Swedish, English, Hong Kong, Singapore, and China). These central banks agreed to share best practices on climate change related issues a voluntary basis. By June 2023 NGFS had 127 central banks and financial regulatory agencies as its members (NGFS, 2023).

The pressure on central banks has also taken the form of public, media, and expert opinions, as the consequences of climate change have gradually arrived at the doorstep of central banks, including the ECB. During the summer of 2018, for example, drought led to low waters, and cargo ships were not able to travel on the Rhein, leading to fuel shortages in southern Germany (Süddeutsche Zeitung, 2018). Another factor was the criticism that the quantitative easing (QE) programmes of central banks, including the ECB have been overwhelmingly skewed towards high greenhouse gas emitters (Matikainen et al., 2017). With central banks becoming central to the allocation of growing financial resources, demands that they should explicitly include the climate agenda in their strategies became widespread. As a result of all these pressures, the ECB Strategy Review of 2021 laid out an action plan to include climate change considerations in the Bank's monetary policy strategy, including regular climate stress testing of the Eurosystem balance sheet from 2023 onwards (ECB, 2021c).

Emerging studies are not unanimous in welcoming central banks' engagement in the climate change policy. Cullen (2023) questioned whether central bank policies addressing climate change could ever be effective. Christophers (2017) criticised climate risk disclosures as a tool of neoliberal governance, based on false beliefs in markets efficiently incorporating such information. Our goal in this paper is not to judge such policies and their effectiveness, but to uncover the spatio-temporal dynamics of central bank engagement with climate change risks in terms of their impacts on financial stability. To this end we build on literature in economic and financial geography.

To start with, we understand finance in the light of literature on socio-technical systems (Geels, 2005) as a socio-technical regime, based on seven interconnected pillars of financial firms, regulation, policy, technology, market and user preferences, as well as the science and cultures of finance (Urban &Wójcik, 2019). The system is capable of innovation, constantly producing new financial services, but changing the system as a whole, and moving its socio-technical regime from finance as we know it to sustainable finance, is difficult, complex, and takes a long time. This is because the building blocks of finance as a socio-technical system are tightly interrelated in terms of functions even if they can vary across space in terms of forms. For example, the science of neoclassical finance with modern portfolio theory and efficient market hypothesis in the lead (see e.g. Clark & Wójcik, 2024) encourages market and user preferences for chasing short-term returns, which are in turn facilitated by short-term reporting (as part of regulation) and reflected in the culture of short-term performance incentives. What can facilitate such transition are changes in the broader environment of finance, e.g. the reality of climate change and its consequences, but what is necessary are also specific innovations. These can start as disjointed niche initiatives, but as they grow and link together, and put pressure on all building blocks of the existing socio-technical regime of finance, they may gradually challenge and replace it.

In the light of this definition, consider that central banking, a major building block of the current socio-technical regime of finance, has also been subject to innovation. Central bank mandates themselves are not set in stone but are the product of specific spatio-temporal contexts. The inflationary contexts of the 1970s and the 1980s in North America, Western Europe and beyond made the mandates

of many central focus on price stability. However, in the wake of the global financial crisis of 2008, financial stability was elevated to a concept of similar merit, making regular financial stability reporting a widespread practice among central banks (Issing et al., 2009).

What can we expect the evolution and geography of central banks' engagement with climate change, conceptualized as niche innovations, to look like? Innovations can come from the geographical and institutional centre of the existing regime or from its periphery. On the one hand, financial centres, where central banks typically reside, are places of financial expertise capable of generating niche innovations. Knox-Hayes (2009), for example, found that the first successful carbon markets were created where service providers with complementary skills were present, and where knowledge transfer was made easier by frequent interactions among market and other players, notably, in London and New York. On the other hand, inertia in the centre may be strong, and smaller, more peripheral, centres can stimulate innovation as they seek innovation to disrupt the status quo. Innovation may also be stimulated in more peripheral financial centres if they are exposed to changes in the environment of the existing regime, e.g. to disruptive impacts of climate change, such as flooding. Our first hypothesis is therefore to expect the first appearance of innovations related to climate change risk analysis in regions where climate threat is rampant, and not necessarily in leading financial centres.

Once a niche innovation emerges, its spread and impact depend on proximity. However, physical or "geographical proximity per se is neither a necessary nor a sufficient condition for learning to take place" (Boschma, 2005, 61). First, to learn from each other people need cognitive proximity – they must share the same knowledge base, as it helps them to communicate, understand, and process new knowledge successfully. However, when cognitive proximity (and overlap in knowledge) is too large, this limits potential for new knowledge, with too much silo thinking. Central bankers in Europe can certainly be expected to have much cognitive proximity, with overlapping knowledge, as most are likely to have background in economics (or law) and experience in the financial sector. One may rather question whether such a degree of cognitive proximity, with few geographers and environmental scientists working in central banks, does not stifle learning about the impacts of climate change.

Second, organisational proximity concerns relations within and among organisations, with loose arrangements and arms-length market transactions on one, and tight hierarchy within an organization on the other extreme (Boschma, 2005). Organizational proximity is inherent to the European System of Central Banks (ESCB), a platform for all central bankers in the EU, and more notably, to the European Central Bank (ECB). All EU nationals are eligible to work in and all EU countries have relations with the ECB. Despite that, the ECB represents a tighter community for Eurozone member countries. For example, the Governing Council, the main decision-making body of the ECB, consists of the governors of the Eurozone national central banks, in addition to its Executive Board members (Clark, 2015).

Third, social proximity refers to socially embedded relations among agents i.e. those involving trust based on friendship, kinship, and experience. While standardized knowledge can be exchanged without trust, the latter is required to exchange tacit knowledge. Social proximity may be sparked by organizational proximity, frequent work-related interactions at conferences, in expert groups of the ESCB and on the job at the ECB, just to name a few opportunities. These, put together, lead to the second hypothesis of this paper: we expect climate risk related innovation to spread quicker among Eurozone members than among other ESCB members thanks to the more closely-knit community of its actors.

Finally, institutional proximity concerns shared values, norms (informal institutions), laws and rules (formal institutions) at the macro-level. As such, it provides a stable environment and social cohesion conducive to interactive learning and innovation.

More specifically, the institutionalization of an innovation brings actors closer to each other and fosters future collaboration. One former example for this is provided by Bieri (2009), who described the geographical spread and the global acceptance of the bank risk regulatory framework, coordinated by a central institution, widely known for its location as the Basel-process. Our third hypothesis rests on this recognition, and provides evidence for the.

spatial institutionalization of an innovation. It is expected to gravitate towards its institutional centre, with a central institution collecting and aggregating

the technical-institutional innovation. While the ultimate determinant of institutional proximity in European central banking is the EU, to a significant extent its forces are projected via its central element, the ECB, which we expect to move to the main stage in the spread of climate risk analysis with time.

Policy makers have been working to eliminate the impact of physical distance from the institutional geography of central banking within the EU: they have been creating opportunities to compensate for it with temporary physical proximity, as well as meetings and co-working enabled by the intensive use of digital technologies. Despite that, all types of distances, particularly institutional and organizational, rise dramatically as one moves from the Eurozone to other central banks of EU member states, and then to European central banks outside the EU. Admittedly, there are forces and opportunities of proximity, including joint workshops and technical assistance programmes to support countries waiting for EU accession (like with Ukraine and Moldova), and at international central bank organisations such as the Bank for International Settlements (Bieri, 2009). However, as this paper illustrates by analysing the usage patterns of climate change risk analytical techniques, these activities have still not eliminated the significance of various forms of distance.

Data and methodology

Financial stability reports

To understand the geography of climate change risk analysis, we looked at the FSRs of central banks in Europe. One may debate if FSRs are the right kind of publications to study the ways central banks discuss climate change risk. Admittedly, climate risks can be analyzed in a macroeconomic setting, which are not necessarily central to FSRs. Sovereigns are at risk of default as a result of climate change (Volz et al., 2020); and macro models with sectoral breakdowns can be powerful tools for macroeconomic analysis, examining the impact of climate change on GDP, inflation and other macroeconomic variables (CamEcon, 2021). The rising significance of financial stability in central bank mandates and modelling efforts after the crisis of 2008, however, tilted climate change analysis towards a financial stability perspective.

Financial stability, the ability of the state in which the "*financial system […] is capable of withstanding shocks and the unravelling of financial imbalances"* (ECB, 2016),[1] is assessed in FSRs[2] by most central banks. An FSR is a "*vehicle to allow stakeholders to form a view about how effectively the central bank is undertaking its broader financial stability responsibilities*" (Allen et al., 2004). It usually consists of'core' and'non-core' parts, whereby core-sections cover the same topics from issue to issue, and non-core parts include results from special and occasional studies (Cihák, 2006).

An FSR has a limited size, hence its contents an indication for the relative importance of matters, as seen by the team responsible for analysing financial stability. Admittedly, the implications of an urgent phenomenon may dominate the pages over long term but unfortunately serious but seemingly less urgent matters such as the climate crisis do not. In addition, these reports are written by a limited number of people within a limited timeframe. For instance, Brexit-related challenges or the energy crisis triggered by the war in Ukraine made several financial stability teams recalculate default probability estimations, which simply used the time and space from climate risk analysis.

The Task Force on Climate-related Financial Disclosures categorizes climate risks into physical risks, defined as the damage or complete destruction of physical assets stemming from climate change induced weather events, and transition risks, which accompany the transition to a low- or zero carbon economy. Both acute physical risks, which are event driven, and chronic risks, which result from long-term

[1] The World Bank, the Bank of England, the De Nederlandsche Bank and the Magyar Nemzeti Bank all define financial stability in a similar spirit.

[2] Some central banks use a different name for FSRs but report on similar topics. The Banque de France, for instance, produces a journal-like Financial Stability Review, whereby each issue is dedicated to a special topic, and its chapters are basically academic research papers. Its 2019 issue focused on climate change and greening of the financial system with an impressive set of analyses and papers. In contrast, the French report on financial stability is referred to as the 'Assessment of Risks to the French Financial System', which we denote as FSR in this paper. Similarly, the Banco de España has a Financial Stability Review (the more journal-like publication) and a Financial Stability Report on the state of the financial system. We refer to this latter as FSR.

Table 1 Countries included in the analysis

Countries	Number of national banks
All EU-member countries, apart from Bulgaria, for which we did not find FSRs in English	26
ECB	1
Non-EU European countries with central banks: Albania, Bosnia-Herzegovina, Iceland, Kosovo, Montenegro, North Macedonia, Norway, Serbia, Switzerland, UK, Ukraine	11
TOTAL	**38**

shifts in climate patterns, such as sea level rise (TCFD, 2017), may diminish or destroy a borrower firm or individual's ability to repay its loan obligation on time (increase their 'probability of default' values), and increase the 'loss given default' values, both of which are core concepts in a typical analysis in FSRs within the Basel Risk Regulatory Framework (Aspachs et al., 2006). Similarly, transition risks, such as investments in low- or zero emission production techniques, house insulations, or even climate-related litigation costs affect future credit quality.

To add another argument for studying FSRs in the context of climate risk analysis by central banks, Pointner et al. (2019) summarize the relationship between further Basel III-risk types, typical concepts in financial stability reports, and physical risks. They concede that market risk (increased price volatility due to disasters), liquidity risk (sudden withdrawals, high demand for emergency loans), operational risk (destruction of banking infrastructure), reputational risk and systemic risk (rising correlation of defaults, underestimation of natural disasters) may all be results of sudden, acute physical disasters.

The data

We manually downloaded[3] 941 FSRs of 38 central banks from Europe using the central banks' publicly available websites (Table 1). We collected FSRs from the earliest date we found them online, until the end of 2022. While most of FSRs are available in English, there are exceptions. The Banque Centrale du Luxembourg publishes in French only (we translated their bigrams into English). Each of the 38 central banks publish one or two FSRs every year, or none,[4] and their length varies between a few and 200 pages.

We analysed bigrams and references in the FSRs. First, we scanned the FSRs for climate change related expressions and counted them, using a few dozen lines of code in R.[5] Since all FSRs come in a pdf format with ASCII coding, the data generated exhibit high accuracy. A few inaccuracies were detected: (1) with words added to graphs, (2) special characters used (such as the El Niño) or (3) where the words were separated (such as cli-mate). To ensure the veracity of our data we went through all of the FSRs of the most important central banks, checked other central banks where no climate-relevant information was indicated by the data; and read the pages where climate-relevant text was found. This latter was also crucial to obtain a general understanding of the spatio-temporal process.

Climate-relevant expressions are best captured as bigrams, or two consecutive words, such as 'physical risks', 'hot house' (a scenario defined by NGFS), 'green bonds' or 'climate stress'. The use of its monogram versions, or single words, can appear in other contexts, such as 'physical money' or 'economic climate', and would distort the analysis. Bigram search

[3] Given the variety of ways FSRs are stored, automating this step would have been a struggle. Downloading them manually was also rather tedious.

[4] For instance, the Bundesbank did not publish a financial stability report in the crisis year of 2008, or the Croatian National Bank FSR is not available on their website in English for 2020. Another peculiarity is Greece, where their Central Bank did not publish a traditional FSR during the recovery phase from the crisis during most of the 2010s. The Central Bank of Ireland started publishing an FSR in 2019 only. The links to the FSRs prior to 2019 of Central Bank of the Republic of Kosovo were broken on their website. Moreover, we were not able to find a map (shapefile) that recognizes the country.

[5] Text extraction was carried out using the pdftools package in R (Ooms, 2023).

is a widely accepted way of analyzing cultural tendencies in books (Michel et al., 2011) or in bibliographic databases and journal archives (Chumtong & Kaldewey, 2017). Financial geographers have also used bigram frequencies (Clark et al., 2015).

Relevant bigrams were identified using two sources. First, we used journal papers and central bank documents most often cited by FSRs' climate change sections, which specifically focus on the modelling questions and financial implications of climate change.[6] These documents were selected either because they are the most often cited documents by FSRs or we found them relevant during the literature review. From these documents, we selected the top two thousand most frequent bigrams,[7] after removing stop words,[8] and expression stemming[9] (removal of endings). Then we manually flagged climate change relevant items among the most frequent bigrams. The second source were the most relevant bigrams from the journal *Nature Climate Change* between 1990 and 2014, as identified and listed by Hamed et al. (2015). The reason for the use of a second source is to counter any criticism of a potential bias in the papers we used to learn relevant bigrams. Admittedly, there is *some* overlap between the authors of the climate-relevant FSR sections and the authors of these papers, who may use their own vocabulary in both. We counterbalance this potential effect by including bigrams from *Nature Climate Change*. The final bigram list is included in the Appendix, which shows bigrams analysed in the following sections.

In the next step, we classified each bigram in the learner set manually based on whether it related to physical risks (P), transition risks (T) or both (B). Finally, we counted the number of bigram appearances within the FSRs, and aggregated the results for each year.

The second part of the analysis involved the opening of all relevant FSRs, and manually collecting references from the sections discussing climate change. This way, a table was constructed with the FSR's publication year, the title of publication, its year and institution of publication, containing a total of 587 references. We also added an additional variable to record if the publication is available from a central bank (not just FSRs but working papers and other publications[10]), from a scientific journal or at any other institution.

Tracing climate change risk considerations over time

The results of the climate change related bigram search by central bank are presented in Fig. 1. It shows low occurrences up until 2018, when the first wave of attention to climate change risks is led by the Dutch and the Belgian National Banks, later followed by a more prominent presence of climate-related issues in other central banks' FSRs.

Until the mid-2010s, FSRs discussed natural disasters as deplorable events which are regrettably parts of life. The first larger bigram clustering is observable in the FSR of the Österreichische Nationalbank, Austria (ÖNB), in 2002. Their second FSR in that year discussed the financial consequences of the devastating floods of 2002. In a stark contrast to the way today's FSRs capture climate change physical risks, the implications of the flood are discussed as a macroeconomic shock: "*the flood is a typical example of a negative supply shock, as it damaged important infrastructural facilities, caused crop failures, destroyed production sites or forced temporary interruptions in production*" (ÖNB FSR, 2002/2, p. 29). The report notes that negative supply shocks caused by natural disasters are often followed by positive demand shocks, triggered by the reconstruction. "*Economic growth in Austria is going to decline by 0.12% in 2002 vis-a '-vis the baseline scenario, but is expected*

[6] DNB (2017), Vermeulen et al (2018), Batten et al. (2016), Battistion et al. (2017), BIS (2021), Behnam and Litterman (2020), Chenet et al (2019), Dikau and Volz (2021), Durrani et al. (2020), ECB (2021b, 2021c), Kemp (2021), Kemp et al (2022), Keenan (2019), Keenan and Bradt (2020), Hudson et al (2019), Gray (2021), Alogoskoufis et al. (2021).

[7] The term frequency – inverse term frequency approach (tf-idf), widely used to identify the most important words (or bigrams) in a document, delivered considerably less climate change relevant top candidates than the method described above.

[8] Stop words are words such as 'the', 'or', 'and', taken from the *tidytext* library, which combines three distinct lexicons, and lists altogether 1149 stop words (Silge and Robinson, 2016).

[9] Using Dr. Martin Porter's stemming algorithm, implemented by the SnowballC R package (Bouchet-Valat, 2020).

[10] For instance, Vermeulen et al (2018) is attributed to the DNB.

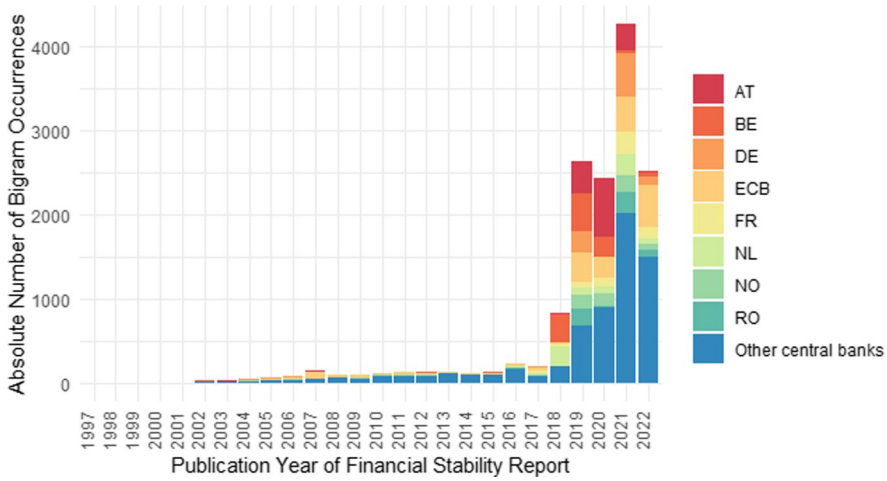

Fig. 1 Absolute number of climate change-related bigram occurrences in FSRs of selected central banks of Europe

to be 0.2% to 0.3% higher in 2003 owing to investments", without any reference to Basel-type concepts such as financial stability or default probabilities, and without the introduction of new innovations.

ECB FSRs mention climate related concepts (hurricanes in the Caribbean and on the Atlantic coast of the US) since 2004, the first year an FSR is available on their website. The likely reason behind this attention is that at the time, five of the ten largest reinsurers globally were European companies with considerable exposures in North America. Similarly, the increase in climate-related bigrams in 2007 was driven by a longer text box on the relationship between insurance sector and climate change (ECB FSR, June 2007, p. 127). It discussed increased expected losses due to "extreme weather events", stating that *"[i]nsurers and in particular reinsurers can transfer part of the risk associated with natural disasters to the capital markets using instruments such as weather derivatives and catastrophe bonds"*. This seemed to solve the concerns related to financial stability, since "[*t*]*he euro area insurance sector, and in particular the reinsurance segment, is increasingly prepared to handle possible future high-impact, albeit low-probability, events, or several closely spaced events affecting parts of the sector and individual insurers"*.

These quotes illustrate the initial approach to climate change as an insurable risk. As such, the financial system was deemed capable of fending off temporary imbalances without interruptions in crucial services to households and businesses. As the December 2011 FSR stated the *„occurrence of natural catastrophes also enables insurers and reinsurers to increase their prices"*. Meanwhile "*massive tornados that hit the South and Midwest of the United States in April and May, and Australian floods in January 2011 […] and the expected impact of La Niña*[11]" (ECB FSR, Dec. 2011, 109) represented little challenge to the business-as-usual, since its effects were expected to be solved within the financial system.

The Dutch and the Belgian National Banks' FSRs represent the most wordcounts in the first year with significant bigram mentions—2018. This turn was not without precedent: the DNB published an exploratory study on the exposure of the Netherlands to climate transition risks only in 2016 (Schotten et al., 2016), and as an explanatory summary document on transition and flood risks (DNB, 2017), without any consideration of further physical risk types. The attention to flood risk is certainly the product of the Dutch history of land reclamation from the sea and managing water-related risks, which is expected to worsen as a result of the warming climate.

The DNB published a real climate stress test one year later (Vermeulen et al., 2018), with parts of it cited in the following FSR (DNB FSR, autumn of 2018). The reason for their focus on transition risks and the exclusive attention to flood risk as physical climate risk sheds light on the difficulties involved in

[11] La Niña is an oceanic and atmospheric phenomenon, which includes lower than average sea surface temperatures in the Southern parts of the Pacific Ocean, and usually lasts up to five months. A consequence of the La Niña is an increased hurricane activity in the Atlantic basin, with reduced tropical cyclone activity in the Pacific Ocean.

the calculations which is related to limited data availability. While assessing transition risks requires firm- and household level data on energy mix, intensity and some profit-and-loss calculations only, physical risk estimation requires accurate firm and household location data, sophisticated geographically sensitive models on physical risk exposures to several risk types and damage functions which explain the value loss when a natural catastrophe occurs.

The National Bank of Belgium (NBB) was also among the first to discuss climate change in length. It published a study on the macroeconomic impact of the fight against climate change already in 2011 (Bruggeman, 2011). This was followed by a long climate risk-related discussion in the FSR of 2018. The main difference to the approach of DNB was the NBB's limited contribution to methodological innovations. The NBB FSR of 2018 focused on general economic implications, including a literature review and a brief discussion of financial stability related topics. In comparison, the DNB presented novel results using a new stress testing method, which was a significant a contribution to the climate risk assessment methodology (Vermeulen et al., 2018).

The DNB's involvement confirms our first hypothesis, which stated that a climate change-related threat would ignite the analytical innovation on climate change risks.

Up until 2018, climate-related discussions in the FSRs other than the DNB's accompanied the phenomena of climate change but did not bring real innovation to the table. The early involvement of the Belgian central bank in climate change risk assessment may be related to its physical proximity to the Dutch central bank, and likely interactions between the two, but also to the presence of EU institutions and environmental non-governmental organisations in Brussels.[12] In any case, its novel content in 2018 stayed behind the levels seen at the DNB.

Elsewhere, the FSR of the Bundesbank, Germany, referred to the rising number of natural catastrophes in 2005. Notably, the report indicated the limited ability of the insurance sector to distribute natural catastrophe risks on their own. Instead, it highlighted the need to use catastrophe bonds more intensively, involving other financial participants in physical risk sharing: *"Hurricane Katrina recently highlighted the limits of insurability […] Catastrophe risks […] are transferred to the capital markets through the issuance of bonds. If the loss event occurs, the bondholders' principal and interest, as a rule, pass to the issuer"* (Bundesbank FSR 2005, 88). However, the FSRs of the Bundesbank remained relatively quiet about climate change until 2019. Its 2019 report subsequently described the analytical framework found in other publications, which could be used to measure the financial stability impact of climate change, but stopped short of providing figures or proposing novel approaches.

In a similar vein, the Banque de France first realized the impact of climate change on its reinsurers. It has been discussing the topic in its FSR since 2017 and 2018, followed by a reference to a coordinated work with the NGFS in 2019. However, it only reported on its first results in its June 2021 FSR. Admittedly, the June 2021 FSR summarizes the results of a stress test involving both transition and physical risks.

To analyze spatiotemporal patterns in a more granular manner, Table 2 contains the first year a bigram is mentioned three times or more in a country's FSR. The top row contains the total number of climate-related bigram mentions for a particular country. The first figure column represents the frequency a specific bigram appears in all FSRs. Due to size limitations, only the top countries and top bigrams are displayed. We have determined the column order arbitrarily, to reflect total bigram mentions and temporal patterns.

Table 2 demonstrates that in the year 2019, climate change-related writings appeared in the FSRs of the ECB, France, Austria, UK, Germany, Sweden, Romania, Slovenia, Portugal and Spain. While country-level developments are discussed later, Fig. 2 shows the temporal advantage of the Dutch, Belgian, French Central Banks and the ECB (we refer to them as the "central countries" to the spread of this innovation); as well as of the Eurozone. The green line in shows the share of these banks' climate change-related bigram mentions in their FSRs out of all bigram mentions. It shows that in 2017 and 2018, these were the dominant central banks discussing climate change in

[12] In 2021, for example, ClientEarth, a leading environmental charity sued NBB for failure to take into account environmental protections under EU law in its monetary policy operations (Climate Case Chart, 2023). They withdrew the case in 2022, but it does highlight the role of Brussels as the centre of European lobbying to which the Belgian central bank is exposed.

Table 2 The total number of (stemmed) bigram mentions by country (top row), bigram mentions for the top bigrams (first column) and the first year an FSR mentions a bigram more than three times

		NL	BE	ECB	FR	AT	UK	DE	SE	RS	RO	NO	MT	SI	PT	CZ	LV	EE	ES	FI	IT	LT	IE	CH	XK	HR	PL	SK	IS	BA	MK	AL	UA	HU	ME
		733	1179	1926	603	1478	268	892	494	311	609	657	497	538	352	483	309	354	317	196	231	223	243	135	133	140	170	155	147	115	80	46	85	108	86
bigram	cnt	NL	BE	ECB	FR	AT	UK	DE	SE	RS	RO	NO	MT	SI	PT	CZ	LV	EE	ES	FI	IT	LT	IE	CH	XK	HR	PL	SK	IS	BA	MK	AL	UA	HU	ME
climat chang	1617	2017	2018	2007	2019	2019	2019	2019	2019	2018	2019	2017	2021	2019	2019	2008	2020	2020	2019	2016	2020	2020	2021	2020	2022	2021	2021	2021	2021		2018			2019	
climat relat	951	2018	2018	2019	2019	2019	2019	2019	2018	2020	2019	2019	2021		2021	2022			2019		2020		2021	2020		2021		2021							
climat risk	812	2021	2018	2019	2017	2019	2022	2019	2021	2018	2019	2019	2021	2019		2020	2020	2020	2021		2022	2021	2021	2020	2022	2021			2021		2018				
transit risk	743	2018	2018	2019	2019	2019	2019	2019	2019	2021	2019	2019	2021	2019	2019	2020	2021	2020	2019	2022	2020	2021	2021	2021	2022	2021			2021						
physic risk	491	2018	2018	2019	2019	2019	2019	2019	2019	2021	2019	2019	2021	2019	2019	2020	2020	2020	2019		2020	2021	2021	2020	2022	2021	2021	2021	2021						
water suppli	426		2020	2021		2021				2011		2005	2013	2007				2022	2005						2020	2009	2004	2015		2011				2020	2010
natur ga	393	2022	2020	2006	2021		2002		2021		2014	2006			2022	2022			2022	2022		2022	2022				2006	2021		2010			2016	2007	
natur disast	326	2021	2019	2005	2017	2002				2010		2021		2008		2008		2020				2021					2006			2013					
mitig measur	322		2015	2004		2020				2014			2019	2021	2020		2018		2021			2008			2021				2009					2014	
energi intens	303	2018	2018	2020	2022	2020		2022	2022		2016		2021				2022	2020	2022		2022						2021		2021	2012				2022	
energi effici	268		2019			2020		2021			2021	2022	2021	2009			2020	2016				2014	2022		2022			2022						2022	
energi sector	265			2016	2016		2003	2020			2007	2004	2013			2015	2022	2016	2021	2016	2022	2022			2022			2022				2012	2017		
green bond	244		2018	2019		2020				2021				2019	2019	2021					2021	2022						2021							
climat polici	234	2018		2019	2021	2020		2019			2019		2021		2021			2020		2016				2021											
sustain financ	212		2018	2019		2019					2019	2021	2020	2019	2011	2020	2020	2020																	
fossil fuel	200	2016	2018	2020	2021	2019		2019	2021		2021		2021		2022	2022		2020	2022	2022		2022					2021								
carbon intens	199	2016	2018	2019		2019		2021			2019		2021	2022	2022		2020	2022			2021		2021				2021								
low carbon	194		2018	2019	2019	2019	2019	2019			2019		2021	2019	2019	2021		2020					2021			2021	2021			2018					
carbon price	193	2018		2021		2020		2021				2020									2022														
energi cost	181	2022	2020	2006				2021						2022	2022		2022	2022	2022		2022		2022					2021				2022		2022	

Stemmed bigrams are not the original expressions but word stems (hence 'energi')

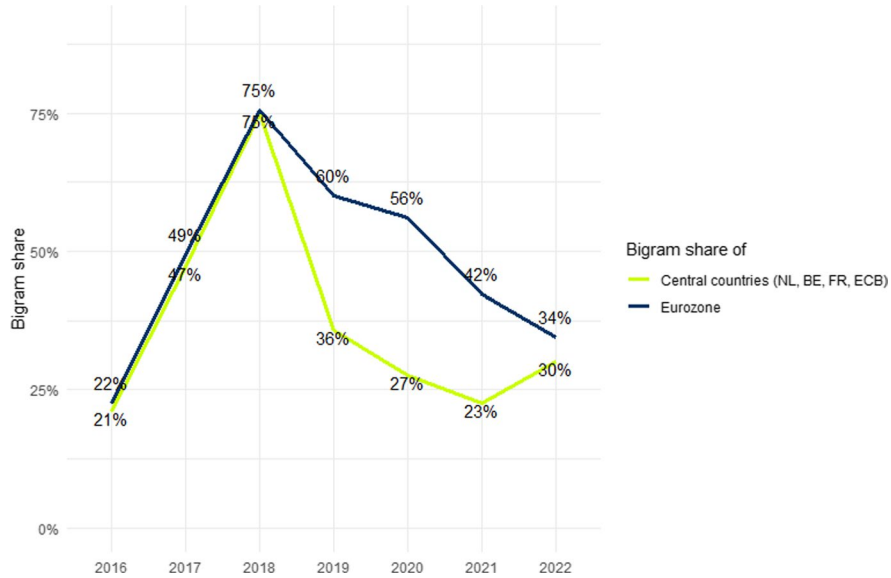

Fig. 2 The combined share of the ECB and the central banks of the Netherlands, Belgium, and France, and the share of the central banks of the Eurozone in all climate change-related bigrams in all European FSRs

their FSRs. Once the diffusion process reached other European countries, in 2019, other Eurozone central banks caught up the pace and joined the exchange (blue line). Subsequently, their relative share diminished as other non-Eurozone countries' national banks started writing on the issue in their FSRs. Figure 2 and Table 2 reinforce our second hypothesis, namely, that after the 2017, the FSRs of Eurozone-countries, and among them, the central countries represented the majority of climate change-related bigram mentions.

Putting the analytical framework to use not only required the development and application of new analytical techniques, but also investment in data collection efforts (as recognized by NGFS, 2022). In the ECB FSR, a special chapter addresses the data-related problem outright in the May 2019 issue. While on the transition risk side the uniform classification of sustainable assets was missing (the EU Taxonomy Regulation came into force in 2020, and its delegated acts in 2022 only), using a benchmark-level emissions intensity and a price for carbon-dioxide quotas is a simple task in terms of data requirements. In contrast, the ECB report refers to the existence of "*measurement gaps"* in *"understanding of exposures of financial institutions to climate change-related risks*" (ECB FSR May 2019 p 121). More specifically, this concerns the location of bank exposures (e.g., where the buildings financed by mortgages are), and their exposures to risks (how much will be damaged). As a result, the report reaches out to aggregated catastrophe loss figures from reinsurers. Two years later, the ECB first climate stress test relied on (still approximated) data provided by the startup *Four Twenty Seven*[13] (ECB, 2021b, c, 30), and modelled corporate exposures to physical climate risks in a simplified fashion (for instance, using headquarters as opposed to actual production sites), omitting residential mortgages entirely.

This problem was also visible on bigram-data: all central banks face the data and methodology related difficulties when assessing the impact of physical risks on bank balance sheets. In fact, only 18 percent of all bigrams are directly related to physical risks, whereas 33 percent cover transition risks (the rest covers general concepts related to both). On country level,[14] most first mover central banks (including NL, BE, ECB and FR) first wrote on transition risks, followed by discussions of physical risks.

In 2021, it was again the DNB that came up with a novel way to calculate exposures: it increased the granularity of its physical risk analysis significantly-unsurprisingly – related to flood risk in the Netherlands. We cite the following quote as a whole to

[13] Later acquired by Moody's.
[14] Looking at the totals for Europe would be distorted by late joiner central banks, which started discussing transition risks first.

illustrate the data-related pain points in such a modelling: *"we have drawn together granular data from a range of individual sources to create a dataset representing over €700 billion in domestic real estate exposures. This includes both regular data that we gather as well as data from a special survey of insurers and pension funds. The picture that emerges is that the majority of real estate is located in parts of the Netherlands that may be affected by flooding. These include both areas which are not protected by flood defence systems (outside the dikes) and parts of the Netherlands that are protected against floods"* (DNB FSR, Autumn 2021).

Mapping climate change risk considerations

To complement the analysis of bigrams over time we use a map showing the number of bigram occurrences between 2000 and 2022 in Fig. 3. The brightest coloured country on the map, with most occurrences, is Austria, where the Österreichische Nationalbank (ÖNB) follows a special structure in its FSRs. The non-core parts of the FSR are basically research papers, and as such, they offer significantly more text than the text boxes of the ECB or other banks. In 2019, ÖNB published a methodological overview of a Basel-conform climate change modelling (Pointner et al., 2019, in ÖNB FSR Dec. 2019), followed by a report on a climate transition stress test in November 2020 (Battiston et al., 2020, in ÖNB FSR, Nov. 2020), and a report on a carbon price shock in 2021 (Guth et al., 2021 in ÖNB FSR Nov 2021).

The second brightest country on the map is Belgium, where the NBB continued to discuss climate change in its FSRs after 2018. However, similarly to their restrained attitude in 2018, their 2019 FSR was limited to the discussion of a survey carried out among commercial banks in Belgium. In 2020, it presented a scenario analysis of a "*potential introduction of a minimum energy performance standard for residential real estate on the banking sector's mortgage portfolio*" (NBB FSR 2020, 147), which resembles to a kind of climate stress test on transition risks.

Another bright country in Fig. 3 is Norway, with the Central Bank of Norway first discussing climate change in its FSR of 2019. While the report states that "*Norway's exposure to direct physical climate change is limited"*, and remains analyzed in a shallow manner only, a lengthy chapter is dedicated to the consequences of a potential drying in oil demand on the country's financial stability (Norges Bank FSR, 2019, 47). This late consideration may be surprising for one of the largest oil-exporting country globally, where the Norges Bank itself runs an investment management fund[15] to invest oil- and gas-related revenues for future generations. The fund has decades-long track record in incorporating environmental (as well as social and governance-related) factors in its decision making (e.g., Clark & Monk, 2010; Reiche, 2008). It is therefore unlikely that the financial stability team of the Norges Bank had not been aware of the salience of the climate issue. Rather than lacking knowledge, relevant departments of Norges Bank probably did not see the point of analysing and presenting climate risk in an FSR.[16] This omission could have also been influenced by the social and organizational distance to the DNB and other innovating central banks.

The limited space dedicated to climate change in the FSRs of the Bank of England (BoE) may also be surprising, with a total of bigram mentions of around 240 (Fig. 3 and Table 2). While the BoE had contributed several innovations to climate risk analysis in the 2010s, its FSRs focused on other, seemingly more urgent matters such as Brexit.[17] The absence of top-down climate analyses is somewhat alleviated by the fact that the bottom-up stress test results, carried out using inputs from supervised banks and insurers, were published in May 2022 (Bank of England, 2022).

There are further surprises in Eastern Europe too. The FSRs of the Romanian Central Bank first referred to measures aiming at reducing greenhouse gas emissions already in 2011. This was a description of a programme financed jointly by the Romanian

[15] With an assets under management of around 1.5 trillion EUR in 2024.

[16] The Norwegian Government first produced a risk assessment on climate change in 2018 only (NOU 2018, 17), which discussed the transition's implications on the Norwegian economy.

[17] The contents of an FSR underscore the relative importance of matters as seen by the team responsible for analyzing financial stability. Moreover, these reports are written by a limited number of people in a limited timeframe. Matters such as Brexit-related calculations or the impac.

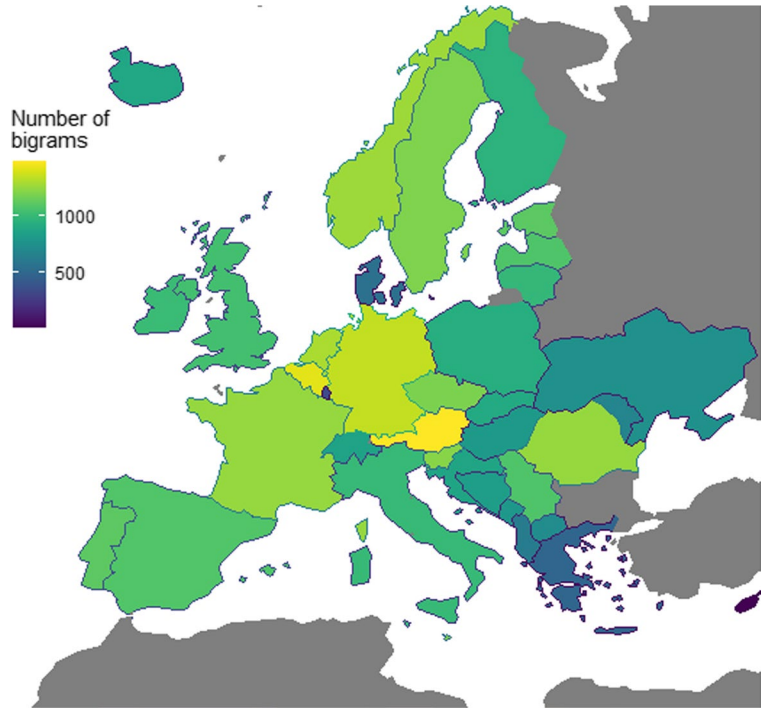

Fig. 3 Number of bigrams in FSRs between 2000 (or earliest available) and 2022. Notes: the map excludes ECB FSRs; Bulgaria does not publish FSRs, Greece started publishing them only recently. Unfortunately, we could not find a shapefile which includes Kosovo

Government, the EU, IMF and the World Bank to improve the country's energy efficiency. In 2019, Romania's FSR mentioned climate change again. The special section of the FSR on climate started with discussing funds the EU had been spending on tackling climate change, followed by a high-level analysis showing the vulnerability of the financial system to climate risks in the country. Elsewhere, Serbia's central bank addressed climate change in the FSRs of 2018 and of 2020. Besides the description of basic ideas and indicators, both reports mentioned credit lines provided by the European Bank for Reconstruction and Development (EBRD). In comparison, Slovenia, a Eurozone member, also dedicated considerable space to the transition risk of its financial sector in its FSR of 2019, admitting that the country had already met the 2030 emissions target in that year.

The sources of climate change risk considerations

The analysis of climate change-related citations in FSRs provides direct evidence on the influence a central bank has on others. Table 3 shows the gradual disappearance of national central banks from the top positions of influence[18]: references to papers and talks published the DNB and the Bank of England dominated FSRs in 2018, including DNB (2017), Schotten et al. (2016) and Vermeulen et al. (2018) for DNB, and speeches of Carney (2015) as well as Batten et al. (2016) for the Bank of England. DNB and BoE positions decline over time and disappeared from top five in 2021 and 2022. Once the community of central banks processed their innovations, approaches and methods to climate change risks underwent coordination, and international bodies grew to dominate the rankings of influence, led by the ECB, Network of Central Banks and Supervisors for Greening the Financial System (NGFS), and Intergovernmental Panel on Climate Change (IPCC). This is direct evidence in favour of our third hypothesis, stating that innovative

[18] An interesting observation on the significance of proximity and distance we made is that we found only two references to writings by the US Federal Reserve (by the Swiss and the Dutch Central Banks), and no reference at all to the influential 'Report of the Climate-Related Market Risk Subcommittee, Market Risk Advisory Committee of the U.S. Commodity Futures Trading Commission' (Behnam and Litterman, 2020). This is despite the fact that its topics are fairly similar to the points discussed by the ECB and other European FSRs. Likewise, there is only one single reference (by the National Bank of Serbia) to an Asian central bank (to the Bangladesh Bank).

Table 3 The most cited references on climate change in European central banks' FSRs

Top five cited institutions (2018 - 2022)				Top five cited institutions in 2018		Top five cited institutions in 2019		Top five cited institutions in 2020		Top five cited institutions in 2021		Top five cited institutions in 2022	
rank	name	count	share	name	count	name	count	name	count	name	count	name	count
1	ECB	68	12%	DNB	11	journal paper	18	ECB, journal paper	14	ECB	21	ECB	24
2	journal paper	68	12%	journal paper	8	Bank of England, NGFS	16	EC	9	journal paper	20	journal paper	8
3	NGFS	45	8%	Bank of England	5	EC	13	NGFS	6	NGFS	17	Banca d'Italia	5
4	EC	35	6%	NGFS	3	DNB, ECB	9	Banca d'Italia, DNB, EIOPA, ESRB, UN	4	IPCC	10	IPCC	4
5	DNB	29	5%	EC, TCFD	2	UN	8	Bank of England, BIS	3	EC	8	BIS, EBA, EC	3

Institutions with the same number of citations are separated with a comma. *BIS* Bank for International Settlements, *EBA* European Banking Authority, *EC* European Commission, *EIOPA* European Insurance and Occupational Pensions Authority, *ESRB* European Systemic Risk Board, *IPCC* Intergovernmental Panel on Climate Change, *TCFD* Task Force on Climate-Related Financial Disclosures

knowledge accumulates at the ECB, from where it gets redistributed again.

The directed graph of references in Fig. 4 zooms in on central bank publications only, visualizing our argument further. The arrows point from central bank FSRs towards other central banks which are referenced. The years represent the publication year of the FSRs. The graph visualizes the centrality of the DNB and the Bank of England in 2018, which only grew stronger in 2019. The pandemic year of 2020 generated a lower number of citations compared to the preceding year. Nevertheless, in that year the ECB became the most cited central bank, and its dominance expanded further in 2021. In 2022 the absolute number of references declined, but the ECB's central location remained unchallenged.

Besides the centralization of citation patterns, the institutional agreement in methodological questions was underscored by the ECB itself: "*a growing body of empirical evidence on climate-related risks to financial stability has now provided a robust analytical foundation for macroprudential policy considerations*" (ECB/ESRB, 2022, 3). The focus has gradually shifted from discussing research to refinement questions, and to regulation. Both ECB/ESRB (2022) and the EBA (2022) papers started studying the ways climate risks can be incorporated into a macroprudential risk framework, implying that the regulators consider options on how higher or lower climate risks in bank portfolios should appear in capital allocation processes. More specifically, the EBA (2022, 12) states, "*[t]he analysis demonstrates that the Pillar 1 framework already includes mechanisms that allow the inclusion of new types of risk drivers such as those related to environmental risks*". Such a regulation on climate risks and capital requirements would move the process of climate risk analysis even higher up the institutional ladder, to the EU legislation level, which would represent an additional centralization of an analytical method which initially started as an innovation outside the centre of the hierarchy.

Conclusions

Our goal was to examine the spatial and temporal process of financial innovation, as climate change risk analytical methods gradually conquered the pages of financial stability reports (FSRs) issued by European central banks. At least three major factors influenced the process: the evolving interpretation of central bank mandates as a result of public pressure, the recognition of the salience of climate change by central banks, and the spread and availability of know-how related to the analysis of physical and transition-related climate change risks.

Our results, based on identifying climate change related mentions and references within 941 FSRs of 38 central banks in Europe, confirmed our three hypotheses. First, we showed that the tipping point

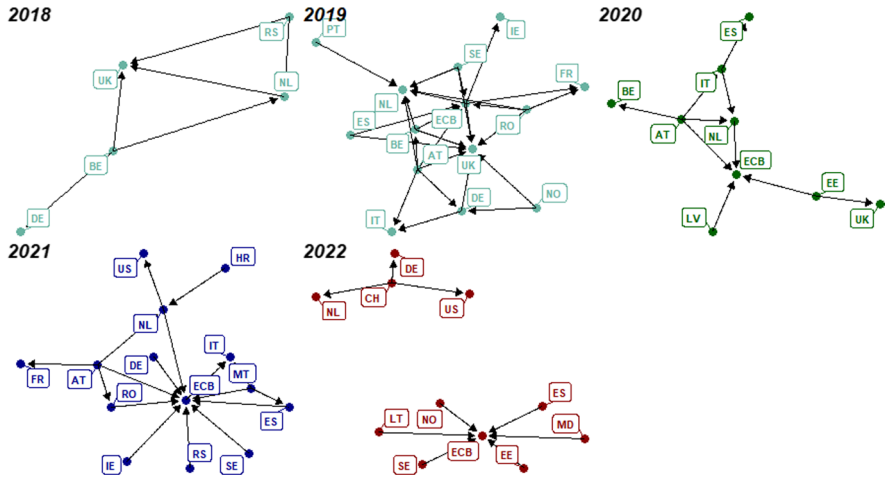

Fig. 4 Citation directions in FSR reports. Notes: Arrows point from the central bank that used a reference in their FSR towards the cited institution. The graph shows the number of links. Lines have the same weight irrespective of the number of citations

in climate risk analysis was the Paris Agreement of 2015, followed by the decisions of elected politicians, among them, MEPs of the European Parliament (EP, 2018), to explicitly instruct central banks to consider climate change in their policies. It was, however, a few central banks influenced less by a narrow interpretation of their mandates and exposed more to climate change threats, among them, the Dutch Central Bank (DNB), which developed methodological innovations and started publishing them.

Second, we showed that physical and organizational proximity mattered in the spread of climate risk analytical techniques. Countries in the proximity of the Netherlands, as well as Eurozone members, were among the first adopters, followed by other countries outside the Eurozone, and the EU. This observation underscored the expectation that distances and geographies matter and have a major role in determining the way European central banks are looking at climate risk exposures.

Third, our analysis of citations and references within FSRs has demonstrated that this successful innovation required the involvement of the centre, with the ECB gradually turning into an aggregator of analytical knowledge, and as a result, serving as a reference point for all central banks pursuing new research and analysis in this area. This centralization ensures the EU-wide acceptance of the results, catalyses communication and cross-country comparisons, as well as makes economies of scale possible. Moving forward, the role the ECB played in the organizational and social acceptance of the results of climate risk analysis may be a prerequisite for a uniform macroprudential treatment of climate change risks within the EU to be reflected in regulation.

To be sure, financial stability reports will not save us from the climate disaster and are only a reflection of whether and how central banks consider climate change risks in their analysis. Nevertheless, in order to make finance, and more specifically, banking an effective player in the arduous journey towards net zero, ideas to be implemented not only require the involvement of its individual actors, but should be catalysed by a flexible central player open to innovation. It can provide fruitful avenues for thought exchange by reducing the effects of geographical distance, and generate positive externalities. Further, such central players may impose regulatory frameworks with success once a mutually acceptable and implementable solution is found and supported by its members.

Appendix

Table 4 The final list of stemmed bigrams (i.e. two consecutive words after the removal of stopwords ('the', 'a', etc.) and word endings) used to identify climate change focus within the FSRs is listed here. We classified each bigram manually if they are transition risk related, physical risk related or both. This list can be used as a reference dictionary in climate change risk related analysis

bigram	risk type
absolut emiss	Transition
action climat	Both
address climat	Both
aerosol impact	Both
agreement target	Both
anthropogen emiss	Transition
assess climat	Both
atlant hurrican	Physical
atmospher carbon	Both
averag emiss	Transition
baselin orderli	Both
biomass burn	Both
blind spot	Both
burn black	Transition
carbon balanc	Transition
carbon border	Transition
carbon budget	Transition
carbon concentr	Both
carbon cycl	Transition
carbon dioxid	Transition
carbon economi	Transition
carbon emiss	Transition
carbon feedback	Both
carbon financ	Transition
carbon footprint	Transition
carbon intens	Transition
carbon neutral	Transition
carbon premium	Transition
carbon price	Transition
carbon risk	Transition
carbon sink	Transition
carbon tax	Transition
carbon taxat	Transition
carbon transit	Transition
cascad climat	Physical
cat model	Physical
cata stroph	Physical
catastroph climat	Physical
catastroph event	Physical
catastroph model	Physical
catastroph risk	Physical
cdr technologi	Transition
challeng climat	Both
challeng polit	
chang climat	Both
chang commun	Both
chang mitig	Physical
chang risk	Both
chronic physic	Physical
citi resili	Physical
clim chang	Both
climat action	Both
climat attribut	Both
climat catastroph	Physical
climat chang	Both
climat crisi	Both
climat damag	Physical
climat data	Physical
climat event	Physical
climat financ	Both
climat hazard	Physical
climat impact	Physical
climat justic	Both
climat mitig	Both
climat model	Physical
climat neutral	Both
climat polici	Both
climat relat	Both
climat respons	Both
climat risk	Both
climat scenario	Both
climat scienc	Both
climat servic	Both
climat shock	Both
climat specif	Both
climat stress	Physical
climat system	Physical

Table 4 (Continued)

bigram	risk type
climat target	Both
climat variabl	Both
climateg inquiri	Both
cloudi pictur	Both
coal mine	Transition
coastal flood	Physical
coastal lender	Physical
coastal properti	Physical
combat climat	Both
consensu predict	Both
conserv measur	Both
cool polar	Physical
damag function	Both
deep ocean	Physical
degre celsiu	Both
delai transit	Both
disast risk	Physical
disclosur tcfd	Transition
disorderli transit	Both
disrupt energi	Transition
dry southern	Physical
dt hhw	Both
durrani volz	Both
earth system	Physical
effect carbon	Transition
embed climat	Both
emiss data	Transition
emiss gap	Transition
emiss intens	Transition
emiss pathwai	Transition
emiss reduct	Transition
emiss target	Transition
emiss trade	Transition
emit firm	Transition
energi consumpt	Transition
energi cost	Transition
energi demand	Transition
energi effici	Transition
energi intens	Transition
energi label	Transition
energi mix	Transition

Table 4 (Continued)

bigram	risk type
energi product	Transition
energi sector	Transition
energi sourc	Transition
energi system	Transition
energi tax	Transition
energi technologi	Transition
energi transit	Transition
environ agenc	Both
environ chang	Both
environ re	Physical
environment chang	Physical
environment extern	Both
environment harm	Both
environment object	Both
environment polici	Both
environment protect	Both
environment qualiti	Both
environment risk	Physical
environment sustain	Both
environment tax	Transition
estim climat	Both
eu emiss	Transition
eu taxonomi	Transition
european environ	Both
european green	Both
explicit carbon	Transition
extrem climat	Physical
extrem heat	Physical
extrem physic	Physical
extrem temperatur	Physical
extrem weather	Physical
fiduciari duti	Both
fight climat	Both
financ emiss	Transition
financ green	Both
fl ga	Both
flood damag	Physical
flood hazard	Physical
flood insur	Physical
flood loss	Physical
flood prone	Physical

Table 4 (Continued)

bigram	risk type
flood protect	Physical
flood risk	Physical
flood scenario	Physical
fluvial flood	Physical
forest carbon	Both
fossil fuel	Transition
fr ngf	Both
fuel sector	Transition
futur climat	Both
futur flood	Physical
ga emiss	Transition
ga ghg	Transition
geograph locat	Physical
ghg concentr	Both
ghg emiss	Transition
global catastroph	Physical
global climat	Both
global emiss	Transition
global forest	Both
global ocean	Physical
global temperatur	Physical
global warm	Both
gradual warm	Both
grai hazard	Both
green activ	Both
green asset	Both
green bank	Both
green bond	Both
green credit	Both
green deal	Both
green financ	Both
green firm	Transition
green growth	Both
green index	Transition
green innov	Transition
green invest	Both
green loan	Both
green qe	Both
green support	Both
green technologi	Both
green transit	Both
green univers	Transition
greener economi	Both

Table 4 (Continued)

bigram	risk type
greenhous ga	Both
greenhous gase	Both
hazard simul	Physical
heat stress	Physical
hhw ot	Both
hhw scenario	Both
hot hous	Both
hot summer	Both
hous world	Both
http www.ipcc.ch	Both
hurrican activ	Physical
hurrican andrew	Physical
hurrican risk	Physical
hurrican season	Physical
ibach urgentem	Both
iipp wp	Both
implicit carbon	Transition
incentivis risk	Both
includ climat	Both
incorpor climat	Both
increas climat	Both
increas flood	Physical
indirect emiss	Both
integr climat	Both
intergovernment panel	Both
intern carbon	Transition
intern energi	Both
irrevers natur	Physical
issu green	Both
level rise	Physical
low carbon	Both
marin invad	Physical
mass extinct	Physical
materi climat	Physical
mitig climat	Physical
mitig measur	Both
monetari green	Both
nat clim	Physical
nat hazard	Physical
nation flood	Physical
natur capit	Both
natur catastroph	Physical
natur climat	Physical

Table 4 (Continued)

bigram	risk type
natur disast	Physical
natur ga	Transition
natur hazard	Physical
nawm model	Physical
ngf climat	Both
ngf scenario	Both
north atlant	Physical
object green	Both
ocean acidif	Physical
ocean warm	Physical
optim carbon	Transition
orderli scenario	Both
orderli transit	Both
pari agreement	Both
past reveal	Both
petroleum agricultur	Transition
physic capit	Physical
physic climat	Physical
physic collater	Physical
physic damag	Physical
physic risk	Physical
polit climat	Both
pollut bond	Both
power plant	Transition
price climat	Both
promot green	Both
public www.nature.com	Both
quantifi climat	Both
reduc emiss	Transition
rel emiss	Transition
renew energi	Both
rise sea	Physical
risk cascad	Physical
risk hot	Both
sea ic	Physical
sea level	Physical
sea surfac	Physical

Table 4 (Continued)

bigram	risk type
snow albedo	Both
solar power	Transition
specif climat	Both
sri strategi	Both
strand asset	Transition
summer extrem	Physical
summer heat	Both
surfac temperatur	Physical
sustain financ	Both
sustain futur	Both
sustain insur	Physical
sustain invest	Transition
system ngf	Both
target power	Transition
temperatur anomali	Physical
temperatur increas	Physical
temperatur rise	Physical
transit cost	Transition
transit disorderli	Both
transit hot	Both
transit polici	Transition
transit risk	Transition
transit scenario	Transition
transit vulner	Transition
tropic cyclon	Physical
u. energi	Both
u. environment	Both
urgentem data	Both
volz ecolog	Both
vulner factor	Physical
water infrastructur	Physical
water suppli	Physical
weather deriv	Physical
weather event	Physical
wide climat	Both
world hot	Both
www.nature.com naturecli-matechang	Both

References

Allen, F., Francke, L., & Swinburne, M. (2004). Assessment of the Riksbank's work on financial stability issues. Penning – och Valutapolitik, 3/2004. Stockholm: Sveriges Riksbank. Retrieved from http://www.riksbank.se/upload/Dokument_riksbank/Kat_AFS/pv04_3_artikel1.pdf

Alogoskoufis, S., Dunz, N., Emambakhsh, T., Hennig, T., Kaijser, M., Kouratzoglou, C., Muñoz M. A., Parisi L., & Salleo, C. (2021). ECB economy-wide climate stress test. ECB Occasional Papers No. 281. Available at https://www.ecb.europa.eu/pub/pdf/scpops/ecb.op281~05a7735b1c.en.pdf

Aspachs, O., Goodhart, C., Segoviano, M., Tsomocos, D., & Zicchino, L. (2006). Searching for a metric for financial stability. LSE Financial Markets Group Special Paper Series No. 167. Available at https://www.fmg.ac.uk/publications/special-papers/searching-metric-financial-stability

Balls, E., Howat, J., & Stansbury, A. (2018). Central bank independence revisited: After the financial crisis, what should a model central bank look like?. M-RCBG Associate Working Paper, No. 87. Available at https://www.ecb.europa.eu/press/key/date/2017/html/sp170330.en.html

Bank of England. (2022). Results of the 2021 Climate Biennial Exploratory Scenario (CBES). Retrieved from https://www.bankofengland.co.uk/stress-testing/2022/results-of-the-2021-climate-biennial-exploratory-scenario, Accessed on the 17th November 2022.

Batten, S., Sowerbutts, R., & Tanaka, M. (2016). Let's talk about the weather: The impact of climate change on central banks. Bank of England Staff Working Paper, No. 603. Available at: https://www.bankofengland.co.uk/working-paper/2016/lets-talk-about-the-weather-the-impact-of-climate-change-on-central-banks

Battistion, S., Guth, M., Monasterolo, I., Neudorfer, B., & Pointner, W. (2020). *Austrian Banks' exposure to climate-related transition risk* (p. 40). Österreichische Nationalbank, Financial Stability Report. Available at: https://www.oenb.at/dam/jcr:4175250d-1563-47e8-8fb7-56d7f548d26f/FSR_40.pdf

Battistion, S., Mandel, A., Monasterolo, I., Schütze, F., & Visentin, G. (2017). A climate stress-test of the financial system. *Nature Climate Change, 7*, 283–288. https://doi.org/10.1038/nclimate3255

Behnam, C. R., & Litterman, B. (2020). Managing climate risk in the U.S. financial system. Report of the Climate-Related Market Risk Subcommittee, Market Risk Advisory Committee of the U.S. Commodity Futures Trading Commission. Retrieved from https://tinyurl.com/458fn3zk

Bieri, D. S. (2009). Financial stability, the Basel process and the new geography of regulation. *Cambridge Journal of Regions, Economy and Society, 2*, 303–331. https://doi.org/10.1093/cjres/rsp004

BIS. (2021). Climate-related financial risks – Measurement methodologies. Retrieved from https://www.bis.org/bcbs/publ/d518.pdf

Boschma, R. (2005). Proximity and innovation: A critical assessment. *Regional Studies, 39*(1), 61–74. https://doi.org/10.1080/0034340052000320887

Bouchet-Valat, M. (2020). SnowballC: Snowball stemmers based on the C 'libstemmer' UTF-8 library. Retrieved from https://CRAN.R-project.org/package=SnowballC

Bruggeman, A. (2011). *The economic impact of the fight against climate change. Economic Review* (ii ed., pp. 59–76). National Bank of Belgium. Available at https://www.nbb.be/en/articles/economic-impact-fight-against-climate-change-1?language=en

CamEcon. (2021). Climate impact assessment for the Central Bank of Hungary. Cambridge Econometrics. Retrieved from https://www.camecon.com/what/our-work/climate-impact-assessment-for-the-central-bank-of-hungary/

Carney, M. (2015). Breaking the tragedy of the horizon – Climate change and financial stability. Speech given by Mark Carney, Governor of the Bank of England, Chairman of the Financial Stability Board, Lloyd's of London, September 29, 2015. Available at https://www.bankofengland.co.uk/speech/2015/breaking-the-tragedy-of-the-horizon-climate-change-and-financial-stability

Chenet, H., Ryan-Collins, J., & van Lerven, F. (2019). Climate-related financial policy in a world of radical uncertainty: Towards a precautionary approach. UCL Institute for Innovation and Public Purpose, Working Paper 2019–13. Available at https://www.ucl.ac.uk/bartlett/public-purpose/sites/public-purpose/files/final_chenet_et_al_climate-related_financial_policy_-_towards_a_precautionary_approach_20_dec.pdf

Christophers, B. (2017). Climate change and financial instability: Risk disclosure and the problematics of neoliberal governance. *Annals of the American Association of Geographers, 107*(5), 1108–1127. https://doi.org/10.1080/24694452.2017.1293502

Chumtong, J., & Kaldewey, D. (2017). Beyond the Google Ngram viewer: Bibliographic databases and journal archives as tools for the quantitative analysis of scientific and meta-scientific concepts. FIW Working paper no. 08. Available at https://www.fiw.uni-bonn.de/medien/publikationen/pdf/working-paper/fiw-working-paper-no-8.pdf

Cihak, M. (2006). How do central banks write on financial stability? IMF Working Papers, 2006(163). https://doi.org/10.5089/9781451864236.001

Clark, G. L., & Hebb, T. (2005). Why should they care? The role of institutional investors in the market for corporate global responsibility. *Environment and Planning A, 37*, 2015–2031.

Clark, G. L. (2015). The geography of the European Central Bank: Form, functions and legitimacy. *Journal of Economic Geography, 15*(5), 855–881. https://doi.org/10.1093/jeg/lbv015

Clark, G. L., Lai, K. P. Y., & Wójcik, D. (2015). Editorial introduction to the special section: Deconstructing offshore finance. *Economic Geography, 91*(3), 237–249.

Clark, G. L. and Monk, A., (2010) The Norwegian Government Pension Fund: Ethics Over Efficiency. Rotman International Journal of Pension Management, Vol. 3, No. 1, 2010, Available at SSRN: https://ssrn.com/abstract=1618834 or https://doi.org/10.2139/ssrn.1618834.

Clark, G. L., & Wójcik, D. (2024). Stylised facts and close dialogue redux. *EPF: Philosophy, Theory, Models, Methods and Practice, 3*(1–2), 29–44.

Climate Case Chart. (2023). ClientEarth v. Belgian National Bank. Retrieved from https://climatecasechart.com/non-us-case/clientearth-v-belgian-national-bank/

Cullen, J. (2023). Central banks and climate change: Mission impossible?, *Journal of Financial Regulation*, *9*(2), 174–209. https://doi.org/10.1093/jfr/fjad003

Dall'Orto Mas, R., Vonessen, B., Fehlker, C., & Arnold, K. (2020). The case for central bank independence. A review of key issues in the international debate. ECB Occasional Paper Series, No 248 from https://www.ecb.europa.eu/pub/pdf/scpops/ecb.op248~28bebb193a.en.pdf

Dikau, S., & Volz, U. (2021). Central bank mandates, sustainability objectives, and the promotion of green finance. Ecological Economics, 184.

DNB. (2017). Waterproof? An exploration of climate-related risks for the Dutch financial sector. De Nederlandsche Bank. Retrieved from https://www.dnb.nl/media/r40dgfap/waterproof-an-exploration-of-climate-related-risks-for-the-dutch-financial-sector.pdf

Durrani, A., Rosmin, M., & Volz, U. (2020). The role of central banks in scaling up sustainable finance - What do monetary authorities in Asia-Pacific think? *Journal of Sustainable Finance and Investment, 10*(2), 92–112. https://doi.org/10.1080/20430795.2020.1715095

EBA. (2022). The role of environmental risks in the prudential framework. Discussion Paper EBA/DP/2022/02. Retrieved from https://www.eba.europa.eu/sites/default/documents/files/document_library/Publications/Discussions/2022/Discussion%20paper%20on%20the%20role%20of%20environmental%20risk%20in%20the%20prudential%20framework/1031947/Discussion%20paper%20on%20role%20of%20ESG%20risks%20in%20prudential%20framework.pdf

ECB. (2016). Financial stability and macroprudential policy – The definition of financial stability. Retrieved from https://www.ecb.europa.eu/ecb/tasks/stability/html/index.en.html

ECB. (2021b). Detailed roadmap of climate change-related actions. Retrieved from https://www.ecb.europa.eu/press/pr/date/2021/html/ecb.pr210708_1_annex~f84ab35968.en.pdf

ECB. (2021c). ECB sets up climate change centre. Retrieved from https://www.ecb.europa.eu/press/pr/date/2021/html/ecb.pr210125_1~3fc4ebb4c6.en.html

ECB/ESRB. (2022). The macroprudential challenge of climate change, July 2022. Retrieved from https://www.esrb.europa.eu/pub/pdf/reports/esrb.ecb.climate_report202207~622b791878.en.pdf

EP. (2018). European Parliament Resolution of 6 February 2018 on the European Central Bank Annual Report for 2016 (2017/2124(INI)). Retrieved from https://www.europarl.europa.eu/doceo/document/TA-8-2018-0025_EN.html

Geels, F. W. (2005). The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). *Technology Analysis and Strategic Management, 17*(4), 445–476.

Gray, I. (2021). Hazardous simulations: Pricing climate risk in US coastal insurance markets. *Economy and Society*. https://doi.org/10.1080/03085147.2020.1853358

Guth, M., Hesse, J., Königswieser, Cs., Krenn, G., Lipp, C., Neudorfer, B., Schneider, M., & Weiss, P. (2021). OeNB climate risk stress test – Modeling a carbon price shock for the Austrian banking sector. Österreichische National bank, Financial Stability Report 42. Available at https://www.oenb.at/dam/jcr:06fa6547-c8c9-4b89-9d2e-a34fc4f21ab1/FSR_42.pdf

Hamed, A. A., Ayer, A. A., Clark, E. M., Irons, E. A., Taylor, G. T., & Zia, A. (2015). Measuring climate change on Twitter using Google's algorithm: Perception and events. *International Journal of Web Information Systems, 11*(4), 527–544. https://doi.org/10.1108/IJWIS-08-2015-0025

Hudson, P., Botzen, W. J. W., & Aerts, J. C. J. H. (2019). Flood insurance arrangements in the European Union for future flood risk under climate and socioeconomic change. *Global Environmental Change, 58*, 101966. https://doi.org/10.1016/j.gloenvcha.2019.101966

Issing, O., Asmussen, J., Krahnen, J. P., Regling, K., Weidmann, J., & White, W. (2009). New financial order recommendations by the Issing Committee Part I (October 2008). Preparing G-20 – Washington, November 15, 2008. Center for Financial Studies, Goethe-Universität Frankfurt. Available at https://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/year/2009/docId/6281

Keenan, J. M. (2019). A climate intelligence arms race in financial markets. *Science, 365*(6459), 1240–3.

Keenan, J. M., & Bradt, J. T. (2020). Underwaterwriting: From theory to empiricism in regional mortgage markets in the U.S. *Climatic Change, 162*(4), 2043–2067. https://doi.org/10.1007/s10584-020-02734-1

Kemp, L. (2021). The cascading climate crisis. COP26 Universities Network Climate Risk Notes, 3. Retrieved from https://www.cambridge.org/engage/coe/article-details/6197895658bc4b31869a0c08

Kemp, L., Xu, C., Depledge, A. J., Ebi, K. L., Gibbins, G., Kohler, T. A., Rockström, J., Scheffer, M., Schellnhuber, H. J., Steffen, W., & Lenton, T. M. (2022). Climate endgame: Exploring catastrophic climate change scenarios. *Proceedings of the National Academy of Sciences, 119*, 34. https://doi.org/10.1073/pnas.2108146119

Knox-Hayes, J. (2009). The developing carbon financial service industry: Expertise, adaptation and complementarity in London and New York. *Journal of Economic Geography, 9*(6), 749–777.

Matikainen, S., Campiglio, E., & Zenghelis, D. (2017). The climate impact of quantitative easing. Policy Paper. The Grantham Research Institute on Climate Change and the Environment, LSE. Available at https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2017/05/ClimateImpactQuantEasing_Matikainen-et-al.pdf

Michel, J. B., Shen, Y. K., Aiden, A. P., Veres, A., Gray, M. K., Brockman, W., The Google Books Team, Pickett, Joseph P., Hoiberg, Dale, Clancy, Dan, Norvig, Peter, Orwant, Jon, Pinker, Steven, Nowak, Martin A., & Aiden, E. L. (2011). Quantitative analysis of culture

using millions of digitized books. *Science, 331*, 176–182. https://doi.org/10.1126/science.1199644

MNB. (2022). Zöld pénzügyi jelentés [Green financial report on Hungarian green finances]. Magyar Nemzeti Bank, Budapest. Available at https://www.mnb.hu/kiadvanyok/jelentesek/zold-penzugyi-jelentes/zold-penzugyi-jelentes-2022-majus

NGFS. (2022). Final report on bridging data gaps. Network for Greening the Financial System Technical Document. Retrieved from https://www.ngfs.net/sites/default/files/medias/documents/final_report_on_bridging_data_gaps.pdf

NGFS. (2023). Information relating to the NGFS current composition (members and observers). Retrieved from https://www.ngfs.net/en/about-us/membership

NOU 2018. (2018). Summary climate risk and the Norwegian economy. Summary of a report from a Commission appointed by Royal Decree on 6 October 2017 to assess climate-related risk factors and their significance for the Norwegian economy. Retrieved from https://www.regjeringen.no/contentassets/c5119502a03145278c33b72d9060fbc9/en-gb/pdfs/nou201820180017000engpdfs.pdf

Ooms, J. (2023) Package 'pdftools' for R. Text Extraction, Rendering and Converting of PDF Documents. Available at: https://CRAN.R-project.org/package=pdftools

Pointner, W., & Ritzberger-Grünwald, D. (2019). Climate change as a risk to financial stability. ÖNB Financial Stability Report 38. Available at https://www.oenb.at/dam/jcr:4491df6c-3671-4f6b-955f-0fb88fc3a3e2/FSR_38.pdf

Reiche, D. (2008) Sovereign wealth funds as a new instrument of climate protection policy? A case study of norway as a pioneer of ethical guidelines for investment policy. CICERO Working Paper 2008:03. Available at https://pub.cicero.oslo.no/cicero-xmlui/handle/11250/192268

Rutten, R. (2016). Beyond proximities: The socio-spatial dynamics of knowledge creation. *Progress in Human Geography, 41*(2), 159–177. https://doi.org/10.1177/0309132516629003

Schotten, G., van Ewijk, S., Regelink, M., Dicou, D., & Kakes, J. (2016). Time for transition: An exploratory study of the transition to a carbon-neutral economy. DNB Occasional Studies Vol. 14 - 2. Netherlands Central Bank. Available at https://www.dnb.nl/media/yyfdcwxx/201603_nr_2_-2016-_time_for_transition_-_an_exploratory_study_of_the_transition_to_a_carbon-neutral_economy.pdf

Silge, J., & Robinson, D. (2016). Tidytext: Text mining and analysis using tidy data principles in R. *Journal of Open Source Software, 1*(3), 37. https://doi.org/10.21105/joss.00037

Simandan, D. (2016). Proximity, subjectivity, and space: Rethinking distance in human geography. *Geoforum, 75*, 249–252. https://doi.org/10.1016/j.geoforum.2016.07.018

Süddeutsche Zeitung. (2018). Rhein-Pegel: Niedrigwasser lässt einzelne Tankstellen leerlaufen. November 7, 2018. Available at https://www.sueddeutsche.de/wirtschaft/benzin-tankstellen-leer-1.4200342

TCFD. (2017). Recommendations of the Task Force on Climate-related Financial Disclosures. Task Force on Climate-Related Financial Disclosures. Retrieved from https://assets.bbhub.io/company/sites/60/2021/10/FINAL-2017-TCFD-Report.pdf

Urban, M., & Wojcik, D. (2019). Dirty banking: Probing the Gap in sustainable finance. *Sustainability, 11*, 1745. https://doi.org/10.3390/su11061745

Vermeulen, R., Schets, E., Lohuis, M., Kolbl, B., Jansen, D.-J., & Heeringa, W. (2018). An energy transition risk stress test for the financial system of the Netherlands. DNB Occasional Studies 1607, Netherlands Central Bank, Research Department. Available at https://www.dnb.nl/media/pdnpdalc/201810_nr-_7_-2018-_an_energy_transition_risk_stress_test_for_the_financial_system_of_the_netherlands.pdf

Volz, U., Beirne, J., Ambrosio Preudhomme, N., Fenton, A., Mazzacurati, E., Renzhi, N., & Stampe, J. (2020). Climate change and sovereign risk. SOAS University of London, Asian development bank institute, world wide fund for nature Singapore, and four twenty seven, London, Tokyo, Singapore, and Berkeley, CA.

Woods, C. (2011). Funding climate change: How pension fund fiduciary duty masks trustee inertia and short-termism. In: J. P. Hawley, S. J. Kamath, & A. T. Williams (Eds.), *Corporate governance failures: The role of institutional investors in the global financial crisis.* University of Pennsylvania Press 2011.