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ABSTRACT

Climate change has been recently recognised as a new source of risk for the financial system. Over the last years, several central banks and financial supervisors have recommended investors and financial institutions to assess their exposure to climate-related financial risks. Central banks and financial supervisors have also started to design scenarios for climate stress tests - to- assess how vulnerable the financial system is to climate change. Nevertheless, the financial community falls short of methodologies that allow the successful analysis of the risks that climate change poses to financial stability. Indeed, the characteristics of climate risks (i.e., deep uncertainty, non-linearity and endogeneity) challenge traditional approaches to macroeconomic and financial risk analysis. Embedding climate change in macroeconomic and financial analysis using innovative perspectives is fundamental for a comprehensive understanding of the macro-financial relevance of climate change. This Special Issue is devoted to the relation between climate risks and financial stability and represents the first comprehensive attempt to fill methodological gaps in this area and to shed light on the financial implications of climate change. It includes original contributions that use a range of methodologies – such as network modelling, dynamic evolutionary macroeconomic modelling and financial econometrics – to analyse climate-related financial risks and the implications of financial policies and instruments aiming at the low-carbon transition. The research insights of these contributions can inform the decisions of central banks and financial supervisors about the integration of climate change considerations into their policies and financial risk assessment.

1. Why a special issue on climate risks and financial stability?

While climate change has been increasingly recognised as a major source of risk for the financial system, and the academic and policy community has started paying growing attention to climate finance, there is still a significant gap in the development of methodologies that allow us to analyse successfully climate-related financial risks. The aim of this special issue of the *Journal of Financial Stability (JFS)* is to address this gap. To our knowledge, this is the first special issue devoted to the relation between climate risks and financial stability. This relation has significant implications for the transition to a low-carbon economy and raises significant methodological issues for the academic community.

First, climate risks' specific characteristics (such as deep uncertainty, non-linearity and endogeneity) pose fundamental challenges to traditional methods for macroeconomic and financial analysis, which are not well-suited to capturing these characteristics. Progress in this field requires that scholars engage with the fundamental questions raised by climate risks, moving beyond the mere rebranding of existing models under the label of "climate change" or "green".

Second, climate change introduces new sources of financial risk. The reason is straightforward and follows from the knowledge on climate change that has been developed in the last two decades (see e.g. IPCC, 2014, 2018). In the absence of sufficient mitigation and adaptation actions, climate change implies an increasing potential for adverse socio-economic impacts because of extreme weather events and other types of hazards, across several economic activities and geographical areas (see physical risks below). Climate policies that would succeed in achieving the low-carbon transition and avoiding catastrophic climate change require a very fast and large transformation of both industrialised and developing economies (e.g. with regard to their energy, production and consumption systems) in the next decade or so. This could generate significant disruption, having adverse impacts on several economic activities and sectors, creating at the same time new opportunities for others (see transition risks below). These economic effects of climate change can lead to adjustments in the value of financial assets owned or issued by corporate and sovereign entities. They can also have an adverse impact on the liabilities of insurance companies and the rate of default on the loans provided by financial institutions. The climate-related financial transmission channels can be amplified due to

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financial interconnectedness (Battiston et al., 2016a) and can have important feedback effects on the real economy.

Indeed, the fact that the physical effects of climate change and the low-carbon transition have fundamental implications for a range of sectors in the economy makes climate risks relevant for the financial stability of individual institutions. Further, because of the correlation of the impacts and the interconnectedness of institutions and economies, climate risk is also relevant for the financial stability at both national and global level.

The implications of climate change for financial stability, in turn, pose significant challenges to central banks and financial regulators (Campiglio et al., 2018). However, until very recently, financial actors and markets seemed not to have internalised the knowledge about climate change risks in prices and risk metrics. Since the 2015 Paris Agreement, the financial sector has been increasingly engaging in the conversation on climate change. Financial supervisors now explicitly recognise climate change as a new source of financial risk (e.g. NGFS, 2019; ECB, 2019; FSB, 2020; Despres and Hiebert, 2020; Alogoskoufis et al., 2021) and a number of initiatives have emerged to encourage the disclosure of climate-related financial risks.

For instance, in 2017, the G20 Financial Stability Board (FSB) launched the Task Force for Climate-Related Financial Disclosure (TCFD) aimed to provide investors with recommendations for disclosing climate change risks in their portfolios. In the same year, a group of central banks and financial supervisors established the Network for Greening the Financial System (NGFS). In 2019, the NGFS recommended the use of climate stress tests for the assessment the financial stability implications of climate risks (NGFS, 2019), and in 2020 provided a set of climate scenarios that investors should consider in their climate financial risk assessments (NGFS, 2020). Today, climate change is an element of the assessment of financial institutions' risk and, going forward, will be part of stress-testing exercises (EIOPA, 2019; Grippa and Mann, 2020).

In 2016, the European Commission (EC) created the High-Level Expert Group on Sustainable Finance (HLEG) that recommended the introduction of standards for the identification of sustainable investments. These recommendations were included in the 2018 EC Action Plan for Sustainable Finance and guided the work of the EC Technical Expert Group on Sustainable Finance (TEG) (see European Commission, 2020) which culminated in the publication of the EU Taxonomy regulation in the *Official Journal of the European Union* in June 2020.[1]

These important and unprecedented international initiatives show how relevant climate change has become for the financial stability agendas and the mandates of financial supervisors. In particular, two channels of risk transmission from climate change to financial stability have gained attention:

- *Climate physical risks:* climate change could damage physical assets and firms' production capacity, increasing the credit risk of banks, inducing financial losses for the insurance sector, and impairing governments' financial position.
- *Climate transition risks:* the transition to a low-carbon economy could lead to unanticipated and sudden adjustments of asset prices (both positive and negative) and changes in defaults for entire asset classes, resulting in financial shocks for asset managers, institutional investors and banks' portfolios.

In the context of climate transition risk, the main threats for financial stability arise from a disorderly transition to a low-carbon economy (NGFS, 2019), i.e. a situation in which investors fail to fully anticipate the impact of the introduction of climate policies on their business models (Monasterolo and Battiston, 2020). Firms whose business and revenues depend on fossil fuel production or utilisation will suffer losses, giving rise to the so-called "stranded assets" (Leaton, 2011; Van der Ploeg and Rezai, 2020). These losses could then negatively affect the value of the firms' financial contracts and of the financial portfolios exposed to those firms, such as bank loans and the equity and bond holdings of pension funds (Battiston et al., 2017; Stolbova et al., 2018; Semieniuk et al., 2020). In addition, the high degree of interconnectedness of financial actors can further amplify losses for individual financial actors and for the financial sector, as it happened during the global financial crisis (Battiston et al., 2012, 2016a; Billio et al., 2012; Haldane and May, 2011).

Despite the sense of urgency and policy relevance of this topic, important gaps remain in the academic research in this area. This special issue aims at filling these gaps by publishing original contributions that shed new light on the sources and the impacts of climate-related financial risks and analyse possible financial policies and financial instruments aiming at mitigating these risks.

In the remainder of this editorial paper, we discuss the key research challenges for the analysis of the relation between climate risks and financial stability (Section 2), we provide an overview of the papers included in the special issue (Section 3) and we outline avenues for future research in the area of climate finance (Section 4).

2. Climate risks and financial stability: key research challenges

The analysis of the macroeconomic impact of climate change has received growing attention in the last decade, with a focus on the physical effects of climate change on the economy (see e.g. Noy, 2009; Burke et al., 2015; Hsiang et al., 2017; Diffenbaugh and Burke, 2019; Hallegatte, 2019). The analysis of the relation between climate risks and financial stability is more recent and is characterised by research gaps in two key areas:

1. The quantitative assessment of the impact of climate physical and transition risks on the macroeconomy and the financial system, considering feedback loops and drivers of amplification.
2. The internalisation of information about climate change in financial valuation and portfolio risk management.

2.1. Macroeconomic and financial impacts of climate change

Addressing the gaps in the first research area requires a careful consideration of the nature of climate risk. The literature has highlighted several distinct features of this risk. First, it has been pointed out that climate risk is systemic and non-linear (Battiston et al., 2017; Monasterolo, 2020a; Dafermos, 2021) and is characterised by fat tails (see e.g. Weitzman, 2009; Ackerman, 2017). This means that, if not timely addressed, it can lead to tipping points in the ecosystem (Steffen et al., 2018; Lenton et al., 2019) that can generate prolonged socio-ecological and economic crises and hysteresis effects that prevent the environmental and economic systems to return to their pre-crisis status, with profound implications for financial stability. It also means that the interconnectedness of actors plays a key role in how this risk materialises; crucially, actions that might be look optimal at the individual level might lead to sub-optimal outcomes at the system level. Second, climate risk is endogenous, meaning that the realisation or not of the worst-case scenarios depends on the perception of risk of the agents involved (e.g. policy makers and investors) and their reaction to this perception (Battiston, 2019). Third, climate risk involves and affects at the same time (through different channels) several dimensions of the food-water-energy nexus, and the socio-economic activities related to that, increasing the complexity of impacts and policy reactions (Howarth and Monasterolo, 2016).

The characteristics of climate risk play an important role in the assessment of the macroeconomic and financial implications of

[1] The regulation can be found at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0852&from=EN

climate change. They influence the design of shock scenarios, the shock transmission channels and the conditions under which climate shocks can lead to amplification and persistence (i.e., reinforcing feedback loops). In this regard, a growing stream of research has highlighted the limits of traditional approaches for the analysis of the macroeconomic and financial impacts of climate change and climate policies (Farmer et al., 2015; Mercure et al., 2016; Stern, 2016; Balint et al., 2017; Dafermos and Nikolaidi, 2019; Monasterolo, 2020a, 2020b). In particular, macroeconomic models like Computable General Equilibrium (CGE) and Dynamic Stochastic General Equilibrium (DSGE) models typically assume that agents have rational expectations, that hysteresis plays no role and that the dynamic evolution of the economy is driven primarily by exogenous shocks. These assumptions are at odds with the deep uncertainty, path dependency and endogeneity that characterise climate risk. Further, these models normally relegate the role of money and finance to the sidelines. Although the financial system has been incorporated in many DSGE models since the global financial crisis (Dou et al., 2020), in the vast majority of these models this has been done in the context of 'financial frictions', without considering the endogenous build-up of financial fragility (Galí, 2018), the endogeneity of money (Jakab and Kumhof, 2019), the interaction among heterogeneous agents (Fagiolo and Roventini, 2017), and financial complexity and interconnectedness (Battiston et al., 2016b). Research has shown that these aspects are particularly important for analysing macrofinancial linkages successfully. Moreover, general equilibrium models cannot capture the interaction between heterogeneous forward-looking expectations about climate scenarios as well as how agents' anticipation of specific scenarios can affect their realisation, giving potentially rise to multiple equilibria.

The aforementioned features of the general equilibrium macroeconomic models limit their ability to assess the financial implications of climate change and the transition to a low-carbon economy.[2] In addition, these models may give a false sense of control over the ability of the economy to switch quickly enough from high to low-carbon investments and to manage climate-related financial risks. This, in turn, could lead investors and policy makers to take sub-optimal decisions at the individual and collective level, with potentially severe implications for financial stability.

On the contrary, stock-flow consistent (SFC) and agent-based models are able to capture the role of non-linearities, interconnectedness, endogeneity and path dependency. They also formulate explicitly the endogenous money creation process which plays a key role in the emergence of financial cycles. Therefore, these models are better suited to analyse the macroeconomic and financial implications of climate risk. This is why they have been increasingly used over the last years for the macro modelling of climate-related financial issues (see e.g. Dafermos et al., 2017; Bovari et al., 2018; Monasterolo and Raberto, 2018; Lamperti et al., 2019).

2.2. Climate change and valuation of financial instruments

Empirical analyses of climate risk pricing in investment decisions and of financial actors' and markets' reaction to climate change are still at an initial stage. A main challenge in this area is the lack of standardised information on the climate relevant characteristics of firms and financial products and the difficulty in identifying low-carbon and high-carbon assets. Environmental Social Governance (ESG) indices that are often used to assess the climate performance of firms suffer from the lack of consistency across financial data providers (see e.g. Berg et al., 2020). The results of several empirical analyses about green bonds – the most well-known green finance instruments – are still inconclusive on whether and under which conditions green bonds have sizeable financial benefits for their issuers (see e.g. Karpf and Mandel, 2018; Zerbib, 2019). Analyses of financial actors' and markets' reactions to climate news and policy announcements show that the financial system has, very recently, potentially started to take climate issues into account (see e.g. Ramelli et al., 2018; Delis et al., 2020; Monasterolo and de Angelis, 2020). However, no definite conclusions can yet been derived since the empirical results on this issue depend on how the climate performance of assets is defined.

A standardised classification of investments that are exposed to the risk of carbon stranded assets is still missing. The EU Taxonomy covers only environmentally sustainable activities. A growing number of rating agencies and financial companies have introduced indicators of environmental performance and carbon intensity which are, however mostly based on backward-looking and self-reported information. Alignment methodologies, such as the Paris Agreement Climate Transition Assessment (PACTA) (see Spuler et al., 2020) can analyse the extent to which financial portfolios are consistent with climate targets using, for instance, information about firms' energy technology and future investment plans. These alignment methodologies have contributed to the development of forward-looking approaches to climate-related financial risks. However, they do not consider how financial risk can materialise across several climate mitigation scenarios (including scenarios of disorderly transition) taking at the same time into account network effects. The Climate Policy Relevant Sectors (CPRS) classification addresses this limitation. The CPRS provides a granular classification of economic activities based on their degree of exposure to climate transition risks, considering their energy technology profile, their role in the energy value chain and their sensitivity to changes in climate policy and regulation (e.g. in terms of costs; see Battiston et al., 2017). Its high degree of granularity by economic activity (NACE 4-digit level) and energy technology (low/high-carbon) allows a direct mapping into the variables of climate economic models, such as the Integrated Assessment Models (IAMs) that have been used in the NGFS climate scenarios (NGFS, 2020). The CPRS classification can also be directly incorporated into financial network models. Several financial institutions, such as the European Central Bank (ECB, 2019), the European Insurance and Occupational Pension Authority (EIOPA, 2019), the Austrian National Bank (Battiston et al., 2020a) and the European Commission (Alessi et al., 2019) have used the CPRS classification to assess European investors' exposure to climate transition risk.

3. This *JFS* special issue on "climate risks and financial stability"

The special issue represents a collection of papers that analyse the relation between climate risks and financial stability using a variety of methodological approaches, including network modelling, mathematical financial modelling, financial econometrics, stock-flow consistent modelling and agent-based approaches. The contributions of the special issue cover (i) the impact of climate transition policies on financial stability, (ii) the physical risks of climate change for the financial system, and (iii) the implications of climate change for pricing in financial markets.

3.1. The impact of climate transition policies on financial stability

Within the theme of climate transition risks, Roncoroni et al., (2021) investigate the impact, in terms of financial stability of banks and investment funds, of the interplay between transition scenarios (derived from the IPCC climate mitigation pathways) and market conditions (i.e. asset price volatility and levels of loss-given-default). In particular, they develop a novel approach that combines the

[2] There are general equilibrium models that have relaxed some of the assumptions mentioned above, like rational expectations (Gelain et al., 2019), the lack of hysteresis (Engler and Tervala, 2018) and the exogeneity of money (Jakab and Kumhof, 2019). However, they have done so by keeping most of the other restrictive features unchanged.

climate stress-test framework (Battiston et al., 2017) with the NEVA framework for Network Valuation of Financial Assets (Barucca et al., 2020) that accounts for asset price volatility and the endogenous recovery rate for interbank assets. They apply this framework to a supervisory dataset of the Mexican financial system, and they show that although the direct exposure of the Mexican financial system to CPRS is small, financial contagion effects can undermine financial stability under scenarios of disorderly transition if accompanied by weak market conditions.

Using SFC modelling, Dafermos and Nikolaidi (2021) and Dunz et al., (2021) analyse the transition effects of climate financial regulation and fiscal policies. They both show that the "green supporting factor" – a financial regulation policy that reduces capital requirements for "green" loans – can increase the financial fragility of banks since it leads to an increase in credit which is supported by less bank capital. Dafermos and Nikolaidi (2021) find that these transition effects of the green supporting factor are reinforced when the green supporting factor is combined with green fiscal policy (carbon taxes and green subsidies). They also find that a "dirty penalising factor" – a financial regulation policy that reduces capital requirements for loans with a negative environmental impact – can have an adverse impact on the financial position of banks in the short run by increasing the default rate of the non-financial corporate sector.

Regarding carbon taxes, both Dafermos and Nikolaidi (2021) and Dunz et al., (2021) show that carbon tax policies need to be accompanied by governments' "carbon tax revenue recycling" (i.e. the reivestment of carbon tax revenues) in order for the adverse distributional and financial effects of carbon pricing to be minimised. A particular innovation of the model of Dunz et al., (2021) is that it incorporates banks' climate sentiments, i.e. financial actors' expectations on the impact of climate policies on firms' performance. For istance, banks can revise their lending strategy and firms' cost of capital as a consequence of their assessment of firms' exposure to climate risks. This allows, for the first time, to feedback the climate financial risk assessment by financial actors into firms' investments and policy decisions, and thus provides a more realistic understanding of the role of finance in the low-carbon transition. The analysis of Dunz et al., (2021) suggests that, when banks anticipate the increase in the carbon tax by revising their lending behaviour and the cost of debt (by decreasing and increasing the interest rate for low-carbon and high-carbon firms, respectively), they mitigate the impact of the energy transition on financial stability.

3.2. Physical effects of climate change on the financial system

Four papers focus on the theme of physical risks. Dafermos and Nikolaidi (2021) and Lamperti et al., (2021) explore how climate finance policies can reduce the long-run financial instability that stems from climate-related events and the change in climatic conditions. Dafermos and Nikolaidi (2021) show that the green supporting and the dirty penalising factor can reduce physical risks since they lower carbon emissions by increasing credit availability for green investment and reducing credit availability for carbon-intensive investment. The impact is quantitatively small but is reinforced when the green supporting and the dirty penalising factor are implemented simultaneously. Using an agent-based macroeconomic model, Lamperti et al., (2021) find that policies that relax bank capital constraints for green loans can have more substantial beneficial effects on physical risks when they are implemented in conjunction with credit guarantees for green loans and carbon risk adjustments in banks' credit rating.

Garbarino and Guin (2021) investigate how banks reacted to a severe flood event in England in 2013–2014. Their results show that banks did not take *ex post* into account flood risk in their valuation for mortgage refinancing and in their decisions about the level of the interest rate and amount of credit provision. A potential reason for that is that banks interpreted the flood event as a one-off occurrence. This indicates that the pricing of physical risks in mortgage lending has probably been limited so far.

Flori et al., (2021) explore empirically the interactions between commodity prices, climate-related variables (like rainfall and temperature) and an index that measures the degree of financial distress in capital markets. They do so by using a combination of a multidimensional graph-theoretical approach with standard econometric techniques. Their results suggest that climate-related variables affect financial stability through the impact that they have on commodity prices.

3.3. Implications of climate change for pricing in financial markets

The implications of climate change for the pricing in financial markets has been investigated in four papers of the special issue. Agliardi and Agliardi (2021) and Fatica et al., (2021) focus on the bond markets. Agliardi and Agliardi (2021) develop a model for defaultable bonds where transition risks are captured via a compound Poisson process. They show how bond prices can be affected by an abrupt change in climate policies that takes the form of downward jumps in the value of firms, thus affecting their default probability. Fatica et al., (2021) investigate econometrically if bonds' yields at issuance are lower for green bonds compared to conventional bonds. They find heterogeneous effects: while yields are lower for supranational institutions and non-financial corporations, there is no difference between the yields of green bonds and conventional bonds in the case of financial institutions. They also find that green bond yields are lower in the case of repeated issuers of green bonds and when there is an external review of the green bond certification process. An additional finding is that those banks that issue green bonds tend to reduce their lending to carbon-intensive sectors.

Alessi et al., (2021) concentrate on the stock markets. Using a sample of companies listed on the STOXX Europe Total Market Index, they first show that investors accept a lower compensation for holding stocks of companies that disclose environmental data and have a lower emission intensity. They then estimate the losses of institutional sectors at the global level under a scenario in which the stocks of companies that have a strong environmental and disclosure profile outperform the stocks of carbon-intensive companies. They find that the losses are not quantitatively large, which is partly explained by the fact that their analysis does not consider second-round effects. They also show that a reallocation of portfolios towards greener assets could reduce these losses.

Climate and weather derivatives can be useful financial instruments for hedging climate-related risks. Bressan and Romagnoli (2021) introduce a copula-based pricing methodology for multivariate climate and weather derivatives analysis. Employing data for Italy, they perform an empirical analysis which shows that the choice for the best copula differs depending on the season under analysis. They also illustrate the challenges related to the pricing of the climate and weather derivatives and point out that the mispricing of derivatives can actually increase physical risks, undermining financial stability.

4. Avenues for future research in climate finance

The papers of this special issue pave the way for further research that can fill the remaining gaps in several areas of climate finance, including:

- The systematic incorporation of network financial modelling (Battiston and Martinez-Jaramillo, 2018) into dynamic macroeconomic approaches to climate change. This is particularly important for an integrated analysis of the macrofinancial feedback loops associated with transition and physical risks.

- The more in-depth analysis of the conditions under which finance could be a driver or a barrier to the low-carbon transition. Modelling the ambivalent role of finance in climate mitigation scenarios is fundamental for the identification of climate mitigation pathways that permit the achievement of the targets of the Paris Agreement (Battiston et al., 2021).
- The modelling of the interactions between fiscal, monetary and financial climate policies and the analysis of the implications of these interactions for the financial systems of specific countries.
- The analysis of climate-related financial risks in the context of the COVID-19 crisis and the design of COVID-19 recovery policies that are aligned with climate targets (see e.g. Battiston et al., 2020b).

Overall, this special issue makes a contribution on how research can inform the debate on climate risk and financial stability. Specifically, research on the above areas is key to support the following stakeholders: (i) the *academic community* to provide evidence-based results and support policy makers in the design of effective strategies for addressing climate-related financial risks; (ii) *central banks and financial supervisors* to introduce climate considerations in their financial risk assessment tools (including stress tests) and prudential policies, and to deliver on their price and financial stability mandates in the era of the climate crisis; (iii) *investors* to disclose and assess climate risks in their portfolios and to introduce climate change considerations in their investment decisions; and (iv) *governments* to design effective climate policies for an orderly low-carbon transition, for example in the context of the European Green Deal and the COVID-19 recovery.

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