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Abstract
The assessment of the socio-economic and financial impacts of climate change represents a main source of uncertainty for policy makers and investors. However, traditional climate economics and financial risk models are not properly equipped to consider the characteristics of climate risks and the opportunities from climate-alignment, being constrained by equilibrium conditions and linearity of impacts, as well as by representative agents and intertemporal optimization. Given the closing window of opportunity to achieve the 2°C target, there is an urgent need for a new wave of models able to embrace uncertainty and complexity deriving not only from climate impacts on socio-economic systems, but also from their reaction. In this regard, approaches rooted on evolutionary economics and complexity science could provide complementary insights to traditional climate economics models. This special issue contributes to fill in this knowledge gap by collecting nine papers applying evolutionary and complex systems approaches, and agent-based and network models to climate change economics, presented at the Special Session of the Research Area "Environment-Economics Interactions" of the European Association of Evolutionary Political Economy (EAEPE)'s conference 2016. By introducing conceptual and methodological innovations in climate economics and finance, the nine articles analyse the conditions for effective climate policies and financial instruments to align countries to the global climate targets, compared to the costs of inaction. This information is crucial to support decision-makers in the analysis of climate-finance policies and instruments to foster the transition to a sustainable and inclusive low-carbon economy.

Keywords: climate policy, climate finance, evolutionary economics, agent-based models, complex systems, network models, uncertainty

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1. Introduction

The assessment of the socio-economic and financial impacts of climate change represents a main source of uncertainty for decision makers. It has been increasingly acknowledged that traditional climate economics and financial risk models are not properly equipped to consider the characteristics of climate risks and the opportunities from climate-alignment, being constrained by equilibrium conditions and linearity of impacts, as well as by representative agents and intertemporal optimization (Pindyck 2013, Heal and Millner 2013, Stern 2013).

Hence, given the closing window of opportunity to achieve the 2°C target, there is an urgent need for a new wave of models able to embrace uncertainty and complexity deriving not only from climate impacts on socio-economic systems, but also from their reaction. This requires considering heterogeneity of impacts and non-linearity of agents and system's responses, the possibility of reinforcing and balancing feedbacks, as well as cascade effects and policy path dependency (Farmer et al. 2015, Mercure et al. 2016, Balint et al. 2017, Monasterolo and Raberto 2018). In this regard, approaches rooted on evolutionary economics and complexity science could provide complementary insights to traditional climate economics models (Lamperti et al. 2018a). This special issue contributes to fill in this major knowledge gap.

The last IPCC report pointed out that the gap between action and climate change mitigation targets is widening (Allen et al. 2018). Indeed, global carbon emissions rose again in 2017, after appearing to stabilise, making it very difficult (if not impossible) to limit global temperature increase "well below" 2°C above pre-industrial times, i.e. to implement the Paris Agreement (UNFCCC 2016). Increases in atmospheric Greenhouse Gas (GHG) concentration caused by carbon-intensive human production and consumptions activities are expected to intensify climate hazards to which humanity is vulnerable, thus posing a broad threat to humanity (Mora et al. 2018). Moreover, according to a recent study (BAMS 2018), climate change was responsible for 15 extreme weather events occurred in 2017, including the U.S. Northern Plains and East Africa droughts. Negative socio-economic impacts of climate change are expected to increase the more global temperature exceeds an increase of 1.5°C above pre-industrial times (Burke et al. 2018) and will leave nobody untouched. Coronese et al. (2018) find a rightward shift and a progressive right-tail fattening process of the global distribution of climate-led economic damages, both on yearly and decade aggregated data. Overall, poor and vulnerable households will be hit the most because they live in areas that are highly exposed to climate-related hazards (e.g. sea-level rise and coastal erosion in the Caribbean islands, Bueno et al. 2008), or because they are less able to cope with risk and to adapt (Hallegatte et al. 2018), even in high-income countries such as the USA (Hsiang et al. 2017).

Nevertheless, investments in climate mitigation and adaptation are lagging behind, and ambitious policies and long-term investments ae required to fill in the USD 2.5 trillion (tn) per year gap until 2050 (IRENA-CPI 2018). In particular, the role of fiscal policies and innovation (Stiglitz and Stern 2017), of development banks (Mazzucato and Penna 2018; Griffith-Jones & Ocampo 2018) and eventually of Central Banks is being discussed (Volz 2017, Barkawi 2017). Indeed, there is growing awareness that the alignment of countries' economies to the Paris Agreement would not be possible by relying on market forces alone. This means that voluntary disclosure of climate-relevant information by companies and financial actors, as recommended by the G20's Task Force on Climate Related Financial Disclosure (TCFD 2018) and by the European Commission's High-level Experts Group on Sustainable Finance (HLEG 2018), would not be enough to scale-up the green private and capital investments needed (Monasterolo et al. 2017).

A role for the state in the launch of a "Green New Deal", through the introduction of clear, coherent and coordinated climate policies stimulating large-scale investment in green technologies has been advocated by economists (Lamperti et al. 2018c). Currently, the introduction of a carbon tax, alongside other incentives, is among the most debated climate-aligned measures to decrease emissions from carbon-intensive sectors of economic activity and foster a shift of investments towards low-carbon sectors (Monasterolo and Raberto 2018, NCE 2018, van der Ploeg and Rezai 2019). At the same time, policies aimed at triggering the transition to sustainability must achieve this objective whilst reducing inequality.

However, large uncertainty characterises the design and implementation of climate-aligned policies, both in terms of timing, magnitude and conditions. On the one hand, some countries provide contradictory signals to investors and markets by either withdrawing from the Paris Agreement (e.g. the US administration), by delaying the phasing out of fossil fuel subsidies (Bast et al. 2015, Gerasimchuk et al. 2017), or by keeping very different investment profiles, a green one within the country and a carbon-intensive one in low-income countries, such as China (Monasterolo et al. 2018). As a consequence, despite the commitments to cut emissions signed by most countries with the Paris Agreement, and the publication of their Nationally Determined Contributions (NDC) to climate mitigation and adaptation, most countries' investments and emissions trajectories are still far from those ambitions (UNEP 2018, WRI 2018). At the recent UNFCCC COP24 climate conference of parties held in Katowice (Poland), signatory governments agreed on a rulebook to implement the 2015 Paris Agreement. However, governments were not able to agree on the timely introduction of climate policies required to maintain a high probability to achieve the climate target, nor to foster the radical economic shift needed to go carbon neutral by 2050, also due to the opposition of the US and Brazilian governments. A growing number of studies finds that climate policy uncertainty prevents investors from anticipating the climate policies and from timely adapting their business and portfolios' strategies once the policy is introduced. This means that investors could incur losses related to abrupt price volatility for both low and high-carbon assets (Monasterolo et al. 2017) and eventually to carbon stranded assets (Caldecott 2018). Recent analyses show that financial markets and financial actors are not yet pricing climate change in the value of financial contracts (de Greiff et al. 2018, Morana and Sbrana 2018), despite evidence of higher risk associated to high-carbon indices emerge after the Paris Agreement (Monasterolo and de Angelis 2018). Policy and financial markets' uncertainty contributes to slow down the transition to sustainability, eventually even inducing investors to increase their current and significant exposure to carbon-intensive assets. This could have negative implications for financial stability (ESRB 2016), as shown by the first Climate Stress-test of the financial system by Battiston et al. (2017), which shows that individual investors hold relevant direct exposures to carbon-intensive sectors (up to 45% of the equity portfolio of pension funds), and these exposures could be amplified through reverberation in the network of financial contracts, with potential systemic effects.

With the aim to decrease uncertainty related to green finance and thus helping markets and investors to start pricing climate-related financial risks in their assets evaluations, the European Commission has launched a Technical Experts Group on Sustainable Finance (EC (COM) 97/2018). This is expected to deliver, by June 2019, a European Union (EU) green finance taxonomy and green bonds standards, and to provide recommendations on climate risk disclosure metrics. In this regard, the need for new, forward-looking climate stress-tests was recently recognized by several central banks and financial regulators, which created a Network for Greening the Financial System (NGFS) (2018). Central banks joined the climate risks and financial stability debate back in 2015, when the Governor of the Bank of England, Mark Carney's cornerstone speech at Lloyds warned investors that climate change could affect economic and financial stability through the channels of climate physical risks, climate transition risks and liability risk.

This special issue aims to shed light on these points by collecting nine papers applying evolutionary, institutional and network-based approaches to climate change economics, presented at the Special Session of the Research Area "Environment-Economics Interactions" of the European Association of Evolutionary Political Economy (EAEPE)'s conference 2016[1]. Together, they contribute to analysing the relation between climate change, economics and finance from an evolutionary economics and complexity studies point of view. In particular, they adopt modelling approaches rooted on Stock-Flow Consistent, Agent Based Models and Network Models. By introducing conceptual and methodological innovations in climate economics and finance, the nine articles analyse the conditions for effective climate policies and financial instruments to align countries to the global climate targets. Further, they help identify the opportunities, challenges and potentially unintended effects of climate-aligned measures, compared to the costs of inaction. This information is crucial to support decision-makers in the analysis of climate-finance policies and instruments to foster the transition to a sustainable and inclusive low-carbon economy. Indeed, understanding to what extent single or blended climate-aligned policies could smooth the low-carbon transition, whilst avoiding undesirable effects such as increasing inequality, is fundamental to obtain citizens and investors' support to the transition, as recent events showed in France.

The nine articles are linked by a common line, i.e. that they all embrace complexity in their respective field of analysis. Embracing complexity in the socio-economic and financial analysis of climate change risks and opportunities is crucial for several reasons. On the one hand, it allows consideration of the characteristics of climate change in their analysis of costs and benefits of climate policies, i.e. fat-tailed distribution of impacts (Weitzman 2009, Ackerman 2017) and the non-linearity between anthropogenic action and ecosystems' reaction, potentially leading to tipping points and domino effects, with catastrophic and irreversible effects (Steffen et al. 2018; Lamperti et al. 2018a). Recent scientific research contributed to decrease some of the uncertainty that characterises climate change in terms of timing and magnitude of events and of socio-economic impacts, though significant uncertainties remain (e.g. Drouet and Emmerling 2016, Allen et al. 2018, Burke et al. 2015, 2018, Hsiang et al. 2017, Lamperti et al. 2018b).

[1] Manchester, Nov 3 to Nov 5, 2016.

On the other hand, adopting a complexity approach allows consideration of the emergence of endogenously generated systems crises, identifying the drivers and the appropriate solutions, thus providing decision makers with results to inform the choices that they make. In particular, the modelling approaches based on evolutionary economics and network science could enable us to understand three key features of modern climate-socio-economic systems, i.e. i) the emergence of potentially destabilizing feedback loops across heterogeneous actors and sectors and cascade effects through which risk generating in one sector/agent could be transmitted to (and even amplified in) another sector/agent, within the network of relations; ii) the presence of non-linearities and tipping points in system's reaction to human activities, after which a system changes its core characteristics (Lontzek et al. 2015, Steffen et al. 2015); and iii) the role of path-dependency in policy decisions, where actions introduced with a specific aim could turn out to provide completely different outcomes, which are then difficult to phase out from the system (Sterman 2012). By doing so, they could provide policy-relevant, timely information to support decision makers in policy and finance in the design and implementation of effective climate-aligned policies and financial instruments, considering socio-economic and environmental systems as complex adaptive systems (Lamperti et al. 2018a).

The rest of this introduction to the special issue is organized as follows. Section 2 discusses the contribution of complexity to the analysis of the role of innovation in structural change for the low-carbon transition. Section 3 discusses the results of recent developments and applications of Stock-Flow Consistent, Agent-Based and ecological macroeconomic models for the analysis of climate-aligned policies, while Section 4 presents the contribution of financial and macro-network models. Finally, Section 5 concludes with recommendations for future research in climate economics and finance.

2. Complexity and structural change for the low-carbon transition

The evolutionary economics literature argues for the need to understand the interactions between technological and institutional changes driving structural change in economic systems. Novelties and changes in one system dimension, often resulting from the adaptation and learning behaviours of agents, give rise to selection pressures for changes in other system dimensions, leading to an evolutionary process of transformation of economies. Most famously, Schumpeter (1934, 1942) described this as a process of 'creative destruction', in which new businesses and new industries develop from initial niches to challenge and overthrow existing businesses and industries. A full evolutionary theory of economic change was developed by Nelson and Winter (1982), and this approach has been linked with complex systems ideas to describe how economies have evolved and grown more complex over the long-term (Beinhocker, 2006; Kirman 2010, Nelson et al. 2018, Dosi and Roventini 2019).

More recently, it has been argued that combining insights from evolutionary economics and ecological economics can inform energy and climate policies and the features of a transition to low-carbon economies (Marechal and Lazaric, 2010; Foxon, 2011, 2017). This would bring together insights on complexity and evolutionary change, with understanding of the dependencies of economic activity on energy and materials flows from and to ecosystems.

The papers in this section discuss the relations between evolutionary change, complexity and energy dependence of economic systems in different ways. Savona and Ciarli (2019, this issue) review the *empirical literature* on economic structural change and climate change and derive a number of stylised facts. Building on Csereklyei et al. (2016), they firstly argue that energy use per capita in most countries has increased in proportion to increases in income per capita, leading to only a partial decoupling of energy use and economic growth. Secondly, the transition to a service (tertiary) economy in many industrialised countries has not led to a reduction in material intensity of economic activity, refuting claims of 'de-materialisation'. Thirdly, they find evidence for a displacement of economic activity with high emissions from industrialised to developing countries, so that the latter are 'trading jobs for emissions', meaning that overall global emissions continue to increase. Finally, environmental regulations have been shown to have a positive effect on labour markets and the demand for high skills green jobs.

On the *theoretical side*, Ciarli and Savona (2019, this issue) discuss how different models assessing environmental impact and climate change incorporate structural change in economies. They find that different types of models include different aspects of structural change, in relation to sectoral composition, industrial organisation, technology, employment, final demand and institutions, but that no modelling approach yet successfully incorporates all these aspects. Whilst integrated assessment models (IAM) and computable general equilibrium (CGE) models address few of these types of structural change, structural change models (SCM) focus on the sectoral composition, and Keynesian ecological macroeconomics models (EMK) pay attention to final demand and employment structure. They argue that evolutionary agent-based models (EABM) provide the most promising approach, as they incorporate more of these aspects of structural change and how these emerge from the interactions of microeconomic agents (an example in this special issue is Lamperti et al. 2018b). Further work is needed to more fully represent the interactions between agents, structural change, economic growth and climate change in the next generation of evolutionary complex models.

Keen, Ayres and Standish (2019, this issue) focus on the role of energy in production. They argue that mainstream economic production analysis neglects the important role of energy. Instead, they argue that the usual production inputs of labour and capital should be treated as functions of energy inputs, since "labour without energy is a corpse, whilst capital without energy is a sculpture". To enable this, they use thermodynamic concept of exergy, which is that portion of energy available to do useful work (move things, power devices, etc.) in any energy conversion process, with the remaining energy being lost as waste heat. They then treat the outputs of labour and capital, which feed into the production function, as the potential for useful work. Finally, they measure economic output or GDP in exergy terms as the total useful work produced by the economy. This enables them to define an empirically-grounded, energy-based Cobb-Douglas production function. However, further work is needed to show how GDP measured in exergy terms is related to the standard economic measure of GDP in monetary value terms.

3. Stock-Flow Consistent, Agent-Based and macroecological models for the analysis of climate-aligned policies

Integrated Assessment Models (IAM) are the most used modelling approaches to assess the costs of climate policies compared to the cost of inaction on the climate, see for instance Nordhaus' DICE and RICE models (Nordhaus et al. 1992, 2017), the LIMITS IAMs (Kriegler 2013). Nevertheless, it has been argued that IAMs have "such crucial flaws that they are almost useless as tools for policy analysis" (Pindyck 2013). First, their time and spatial resolution is limited to macro-regions of the world, and future projections of sectors' market share (e.g. renewable energy vs. fossil fuel energy and electricity) are not granular enough for economic cost-benefit analysis. Second, heterogeneity in terms of climate change shocks, and income and technology distribution are overlooked. More generally, such models cannot represent and model heterogeneous interacting firm, households, banks, etc. Third, the financial dimension and monetary flows are completely missing. Nevertheless, the growing financialization of the real economy (Palley 2016) point out the need to connect physical flows with monetary flows in the economy. In this regard, a growing stream of research is contributing to combine evolutionary, ecological economics with Post-Keynesian economics (see Dafermos et al. 2018 in this issue).
Fourth, climate impacts and energy transition risks are often disregarded, thus limiting the scope to the deterministic set ups of the simulation scenarios. This does not allow to account for uncertainty and tipping points which have a fundamental role in coupled climate and economic dynamics. Finally, the ad-hoc choice of the damage function, discount factors, and utility function in IAMs undermines the evaluation of climate impacts and the ensuing policy options (Pindyck 2013).

The fundamental flaws of IAMs require a new approach grounded on complexity science. Balint et al. (2017) provide a survey of the recent developments. The papers in this section of the special issue contribute to push the frontier forward.

The analyses in the papers in this section support the view that the financial mechanisms of endogenous money creation and wealth destruction, and the impact of finance on real economy and on policy feasibility, are crucial to provide a comprehensive assessment of the costs and benefits of climate-aligned policies and instruments. Indeed, they can fundamentally influence the trajectories of (low/high-carbon) sectors' market shares under different climate policy scenarios, in terms of drivers and feasibility of results. So far, IAMs have not been successful in replicating the trajectories of low/high-carbon energy technology occurred in the recent past and are not able to consider the phasing out of specific energy technologies in their future trajectories (e.g. nuclear). Then, finance can induce multiple equilibria or reinforce the gap between multiple equilibria due to the circularity between investments and investors' expectations on climate risks and on the outcome of the policies (Battiston and Monasterolo 2018). Thus, finance can amplify the impacts of policy shocks and create obstacles, ex-ante, to the implementation of policies if there is the expectation that they will lead to uncertainty or abrupt changes in asset values (Monasterolo et al. 2017).

This is an important knowledge gap that needs to be filled. Indeed, not considering the financial sector's role in climate shocks transmission and amplification, could have important consequences for the feasibility of emissions reduction pathways, for policy makers to design and implement timely and effective policies, and for investors to compute their risk adjusted returns accounting for climate risks (see Stolbova et al. (2018) in this issue).

Lamperti et al. (2018b, this issue) develop the first Agent-Based integrated assessment model which provides an alternative to standard computable general equilibrium models. The Dystopian Schumpeter meeting Keynes (DSK) model where heterogenous capital- and consumption-good firms interact in different markets and buy energy from different brown and green plants. The production of goods and energy release GHG emissions which in turn affect temperature dynamics. Technical change is endogenous and affects machine productivity, energy plant efficiency, as well as their emissions. The model generates heterogenous and micro climate damages hitting workers' labour productivity, energy efficiency, capital stock and inventories of firms. Simulation results show larger climate damages than those projected by standard IAMs under comparable scenarios. Moreover, tipping points endogenously emerge, suggesting possible shifts in the growth dynamics, from a self-sustained pattern to stagnation and high volatility, and the need of urgent policy interventions.

The relationship between green innovation and technical change is also explored by Naqvi & Stockhammer (2018, this issue) employing a Stock-Flow Consistent post-Keynesian ecological macroeconomic model. The authors apply the model to analyse two policy experiments which could direct technical change towards sustainable growth, i.e. i) a market-based resource tax (e.g. carbon tax) increase, and ii) a centralized green policy, where public R&D budget is shifted towards resource-saving technologies. Their results suggest that a mix of market-based and centralized policies could be the best solution to foster the low-carbon transition. Indeed, they show that a policy of continuous resource tax growth is needed to induce resource-saving technological change to achieve a greener economy in presence of hysteresis and limited R&D budgets. Further, planned government spending adjustment could spur demand and boost investment.

Dafermos et al. (2018, this issue) develop a Stock-Flow-fund ecological macroeconomic model but they focus on the effects of climate change on financial stability. The model is estimated and calibrated using global data, with simulations conducted for the period 2016–2120. They find that climate change has negative impacts on GDP growth, on bank's leverage and on asset prices in the long-term. On the policy side, the central bank could mitigate climate-induced financial instability by introducing a green QE programme.

Kemp-Benedict (2018, this issue) analyses the climate-finance relation with a Tobin model representing investment-macroeconomic interactions. In particular, the author focuses on the analysis of the role of private investment in a major economic transition, and the role of policy to make green investments attractive to investors. The model includes a distinction between "affected" sectors, which are sensitive to the amount of green capital in the economy because of network effects and forward-backward linkages, and "unaffected" sectors, which are relatively insensitive. The author finds that in a green transition, the affected sector lags the unaffected sector with possible implications for a transition strategy, leading firm and investor to postpone deeper and more systemic changes.

4. The contribution of financial and macro network models for the analysis of financial risks and investment opportunities in the low-carbon transition

This Section presents two novel developments and application of financial and macro-network models for the analysis of the low-carbon transition and the conditions under which climate policies could generate instability in the financial network, with possible cascade effects on the real economy. In that, such models are complementary to those of the previous Section as they shed further light on how different network structures affect the technological diffusion of green technologies or amplify finance shocks related to climate change via reinforcing feedback loops. Climate change impacts, modern economies and the financial system are all characterised by complexity and non-linearity, with which shocks get transmitted to other elements of the system.

Halleck-Vega et al. (2018, this issue) develop a network-based methodology to study the determinants of the formation of technology diffusion networks from the patterns of technology adoption in the case of one of the main technologies for climate mitigation, i.e., wind energy. They find that long-term relationships as measured by economic integration are key drivers of technological diffusions, while specific support measures are less relevant to explain the extensive margin of diffusion. Their results highlight that, on the one hand, the scope of technological diffusion in renewable energy goes well beyond China and India, and that European countries and lack of large hubs among developing countries play a main role in shaping the diffusion process.

Stolbova et al. (2018, this issue) develop a novel methodology based on financial networks and apply it to empirical data of the Euro Area that extends traditional financial network models to include climate risk considerations on financial stability and implications for macro-prudential regulation, based on the literature on complex networks and economic networks (Battiston and Martinez-Jaramillo, 2018). By analysing the transmission throughout the economic sector of positive/negative shocks induced by specific climate policies (e.g. a carbon tax), they identify the reinforcing feedback loops between the financial sector and the real economy that directly affect either the banking sector or non-financial firms. Their methodology helps to overcome the limits of traditional climate economics models that neglect possible feedbacks between sectors thus underestimating the overall policy effects. In addition, it contributes to understand the conditions for virtuous or vicious cycles to arise in the climate-finance nexus, providing a comprehensive assessment of the economic impact of climate policies.

5. Conclusions and research steps ahead

The socio-economic and financial transition path that will be undertaken in the next 12 years will be crucial to allow the achievement of the Paris Agreement targets by 2050. The timely introduction of ambitious climate policies is considered as fundamental to foster green investments and sustainable consumption and production behaviours to create a safe-operating space for human-environmental systems to prosper within the Planetary Boundaries. However, two factors prevent policy-makers to unequivocally commit to the low-carbon transition. First, the growing awareness that late and sudden climate policies will come at a cost, in particular for socio-economic and financial actors that are most exposed to carbon-intensive sectors. Second, the uncertainty that characterises estimates on the short vs long-term costs and benefits associated to specific climate-aligned policies (either fiscal, monetary or regulatory), compared to the costs of inaction. Thus, decreasing the uncertainty associated to the long-term socio-economic and financial implications of the introduction of climate-aligned fiscal and monetary policies, financial regulations and new financial instruments (e.g. green bonds) will be crucial to signal the market and build societal trust towards the credibility of the low-carbon transition.

In this regard, approaches rooted on evolutionary economics and complexity science could provide complementary insights to traditional climate economics and financial risk models by analyzing the micro and macro-level behavior of systems characterized by non-linearity, time dependency and tipping-points.
By contributing to this stream of research, we present nine contributions that differ in terms of the approach embraced - including evolutionary, institutional economics and complexity science - and the modelling solution targeted -either Stock-Flow Consistent models, Agent-Based Models, Network models. Nevertheless, they are tightly connected by a common thread, i.e. the introduction of conceptual and methodological innovations in climate economics and finance to study the conditions for effective climate policies and financial instruments to achieve the global climate targets. By identifying opportunities, challenges, barriers and enablers for scaling-up green investments in economics and finance,
and by disclosing the potentially unintended effects of climate-aligned measures, compared to the costs of inaction, they provide decision-makers crucial information to foster the transition to a sustainable and inclusive low-carbon economy. This information is currently missing, as traditional climate economics and financial models not able to study the characteristics of a system that departs from the conditions of equilibrium and moves towards multiple-equilibria, and the interactions between the micro and macro dimensions of a system. In addition, they exclude the role of finance, which is instead now widely recognised as a potential source of risk as well as a driver of the low-carbon transition.

This special issue opens a research line in this direction. In particular, it contributes to fill in a major knowledge gap on the analysis of the impact of climate-aligned policies (market-based, command-control, monetary policies) on the timing and magnitude of the low-carbon transition in the economic and financial sectors considering the characteristics of complexity and non-linearity of climate impacts, and the heterogeneity of agents' responses under multiple equilibria.

We believe this is only a starting point of a long-term journey in climate economics and finance modelling. Indeed, further policy-relevant research work is needed in the evolutionary and complexity science community to better understand and represent the interactions between climate-aligned policies and the transition of the economy and finance towards sustainability, considering the complexity and non-linearity of climate impacts and of heterogeneous agents' reactions. In addition, the communication of the implications of the models' results in terms of structural change, sustainable growth and climate change, should be improved in order to promote dialogue across socio-economics and finance disciplines, enabling the mutual understanding and usability of results.

6. References

Ackerman, F. (2017). *Worst-Case Economics - Extreme Events in Climate and Finance*. London, New York: Anthem Press.

Allen, M. et al. (2018). Global warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A., & Sapio, A. (2017). Complexity and the economics of climate change: A survey and a look forward. *Ecological Economics*, 138, 252–265.

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

Battiston, S. and Monasterolo, I., 2018. The Climate Target Gap Is Widening. Can We Close It by Including Climate Finance in SSPs?. Can We Close It by Including Climate Finance in SSPs. Available at SSRN, http://dx.doi.org/10.2139/ssrn.3266041

Battiston, S. and Monasterolo, I. (2018b). A carbon risk assessment of central banks' portfolios under a 2°C aligned climate scenarios. Working paper, presented at the first EC TEG-COPFOR conference "Promoting Sustainable Finance", Brussels 9.01.2019 (forthcoming).

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

Battiston, S., D. Delli Gatti, M. Gallegati, B. Greenwals and J. E. Stiglitz (2012). Liaisons dangereuses: Increasing connectivity, risk sharing, and systemic risk. *Journal of Economic Dynamics and Control*, Vol. 36, No. 8, pp. 1121–41.

Beinhocker, E (2006) *The Origin of Wealth: Evolution, Complexity and the Radical Remaking of Economics*. London: Random House.

Bueno, R., Herzfeld, C., Stanton, E. A., & Ackerman, F. (2008). *The Caribbean and climate change*. Somerville, MA: Tufts University.

Burke, M., Davis, W.M. and Diffenbaugh, N.S. (2018). Large potential reduction in economic damages under UN mitigation targets. *Nature*, 557(7706), p.549.

Burke, M., Dykema, J., Lobell, D. B., Miguel, E., & Satyanath, S. (2015). Incorporating climate uncertainty into estimates of climate change impacts. *The Review of Economics and Statistics*, 97(2), 461–471.

Caldecott, B.L. (ed.) (2018) *Stranded assets and the environment: risk, resilience, and opportunity. Routledge, London.*

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

Carney, M. (2015). Breaking the tragedy of the horizon—climate change and financial stability. *Speech given at Lloyd's of London, September*, *29, 2015*.

Ciarli, T. and Savona, M. (2019). Modelling the evolution of economic structure and climate change: a review. *Ecological Economics*, 158, 51-64.

Coronese, M., Chiaromonte, F., Lamperti, F. and Roventini, A. (2018). Natural Disaster Risk and the Distributional Dynamics of Damages. Scuola Superiore Sant'Anna *LEM Working Paper Series* 2018/22. http://www.lem.sssup.it/WPLem/files/2018-22.pdf

Csereklyei, Z., Rubio-Varas, M. de M. and Stern, D.I. (2016). Energy and economic growth: The stylised facts. *Energy Journal* 37(2), 223-255.

Dafermos, Y., Nikolaidi, M., & Galanis, G. (2018). Climate change, financial stability and monetary policy. *Ecological Economics*, 152, 219-234.

de Greiff, K., Delis, M., & Ongena, S. (2018). *Being Stranded on the Carbon Bubble? Climate Policy Risk and the Pricing of Bank Loans*. *CEPR Discussion Papers* (May 2018).

Dosi, G. and Roventini, A. (2019). More is Different ... and Complex! The Case for Agent-Based Macroeconomics. *Journal of Evolutionary Economics*, forthcoming.

Drouet, L. and Emmerling, J., 2016. Climate policy under socio-economic scenario uncertainty. *Environmental Modelling & Software*, 79, pp.334-342.

Farmer, J. D., Hepburn, C., Mealy, P., & Teytelboym, A. (2015). A Third Wave in the Economics of Climate Change. *Environmental and Resource Economics*, *62*(2), 329–357.

Foxon, T.J. (2011). A co-evolutionary framework for analysing transition pathways to a sustainable low carbon economy. *Ecological Economics* 70, 2258-2267.

Foxon, T.J. (2017), *Energy and Economic Growth; Why we need a new pathway to prosperity*, Routledge: Abingdon and New York.

Halleck-Vega, S., Mandel, A. and Millock, K., 2018. Accelerating diffusion of climate-friendly technologies: A network perspective. *Ecological Economics*, *152*, pp.235-245.

Hallegatte, S., Fay, M. and Barbier, E.B., 2018. Poverty and climate change: introduction. *Environment and Development Economics*, 23(3), pp.217-233.

Heal, G. and Millner, A., 2013. Uncertainty and decision in climate change economics (No. w18929). *National Bureau of Economic Research*.

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D.J., Muir-Wood, R., Wilson, P., Oppenheimer, M. and Larsen, K. (2017). Estimating economic damage from climate change in the United States. Science, 356(6345), pp.1362-1369.

Keen, S., Ayres, R.U. and Standish, R. (2019). A Note on the Role of Energy in Production. Ecological Economics, 157, pp.40-46.

Kemp-Benedict, E. (2018). Investing in a green transition. *Ecological Economics*, 153, 218-236.

Kirman, A. P. (2010), *Complex Economics. Individual and Collective Rationality*, Routledge: London.

Kriegler, E., M. Tavoni, T. Aboumahboub, et al. (2013). What does the 2°C target imply for a global climate agreement in 2020? The LIMITS study on Durban Platform scenarios. *Climate Change Economics*, Vol. 4, No. 4, pp. 1–30.

IRENA and CPI (2018). Global Landscape of Renewable Energy Finance, 2018, International Renewable Energy Agency, Abu Dhabi.

Lamperti, F., Monasterolo, I. and Roventini, A. (2018a). *Climate Risks, Economics and Finance: Insights from Complex Systems*. In “The Systemic Turn in Human and Natural Sciences” (pp. 97-119). Springer, Cham.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A. and Sapio, A., (2018b). Faraway, so close: coupled climate and economic dynamics in an agent-based integrated assessment model. *Ecological Economics*, 150, pp.315-339.

Lamperti, F., Mazzucato, M., Roventini, A. and Semieniuk, G. (2018c). The Green Transition: Public Policy, Finance and Innovation, ISIGrowth European Policy Brief, http://www.isigrowth.eu/wp-content/uploads/2018/06/ISIGrowthPolicy_brief_Clima.pdf

Lontzek, T.S., Cai, Y., Judd, K.L. and Lenton, T.M. (2015). Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, 5(5), p.441.

Marechal, K. and Lazaric, N. (2010). Overcoming inertia: Insights from evolutionary economics into improved energy and climate policies. *Climate Policy* 10:1, 103-119.

Mazzucato, M. and Penna, Caetano CR (2018). National Development Banks. In: The Future of National Development Banks.

Mercure, J. F., Pollitt, H., Bassi, A. M., Viruales, J. E., & Edwards, N. R. (2016). Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Global Environmental Change*, *37*, 102–115. https://doi.org/10.1016/j.gloenvcha.2016.02.003

Monasterolo, I., de Angelis, L. (2018). Are financial markets pricing carbon risks after the Paris Agreement? An assessment of low-carbon and carbon-intensive stock market indices. Working paper, available at SSRN, bit.ly/2RLPeND

Monasterolo, I. and Raberto, M. (2018). The EIRIN Flow-of-funds Behavioural Model of Green Fiscal Policies and Green Sovereign Bonds. *Ecological Economics*, *144*, 228–243. https://doi.org/10.1016/j.ecolecon.2017.07.029

Monasterolo, I., Jiani I. Zheng and Battiston, S. (2018). Climate transition risk and development finance: a climate stress-test of China's overseas energy portfolios. *China & World Economy* 26(6), 116–142. Input to the G20 Task Force "An International Financial Architecture for Stability and Development".

Monasterolo, I., Battiston, S., Janetos, A. C., & Zheng, Z. (2017). Vulnerable yet relevant: The two dimensions of climate-related financial disclosure. *Climatic Change*, 145(3–4), 495–507.

Mora, C., Spirandelli, D., Franklin, E.C., Lynham, J., Kantar, M.B., Miles, W., Smith, C.Z., Freel, K., Moy, J., Louis, L.V. and Barba, E.W., 2018. Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nature Climate Change*, 8(12), p.1062.

Morana, C., & Sbrana, G. (2018). Some Financial Implications of Global Warming: An Empirical Assessment (Febr. 2018). Working Paper.

Naqvi, A. and Stockhammer, E. (2018). Directed technological change in a post-Keynesian ecological macromodel. *Ecological Economics*, 154, pp.168-188.

Nelson, R.R., Dosi, G., Helfat, C.E., Pyka, A., Saviotti, P.P., Lee, K., Winter, S.G., Dopfer, K. and Malerba, F. (2018). *Modern evolutionary economics: an overview*. Cambridge University Press.

Network for Greening the Financial System. (NGFS). Retrieved September 12, 2018, from https://www.banque-france.fr/en/financial-stability/international-role/network-greening-financial-system

New Climate Economy (NCE) (2018). Unlocking the inclusive growth story of the 21st century: Accelerating climate action in urgent times.

Nordhaus, W. D. and Moffat, A. (2017). A survey of global impacts of climate change: Replication, survey methods, and a statistical analysis (No. w23646). *National Bureau of Economic Research*.

Nordhaus, W. D. (1992). An optimal transition path for controlling greenhouse gases. *Science*, 258(5086), 1315–1319.

Palley, T., 2016. *Financialization: the economics of finance capital domination*. Springer.

Pindyck, R. S. (2013). Climate change policy: what do the models tell us?. *Journal of Economic Literature*, 51(3), 860-72.

Savona, M., & Ciarli, T. (2019). Structural changes and sustainability. A selected review of the empirical evidence. *Ecological economics*, 159, 244-260.

Schumpeter, J.A. (1934) *The Theory of Economic Development*. Cambridge, MA: Harvard University Press.

Schumpeter, J.A. (1942) *Capitalism, Socialism and Democracy*. New York: Harper & Brothers.

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., … Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(33), 8252–8259. https://doi.org/10.1073/pnas.1810141115

Sterman, J. D. (2012). Sustaining sustainability: creating a systems science in a fragmented academy and polarized world. Sustainability science (pp. 21-58). Springer, New York, NY.

Stern, N. (2013). The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature*, *51*(3), 838–859. https://doi.org/10.1257/jel.51.3.838

Stiglitz, J. and Stern, N. (2017). *Report of the High-Level Commission on Carbon Prices*. International Bank for Reconstruction and Development and International Development Association / The World Bank

Stolbova, V., Monasterolo, I., & Battiston, S. (2018). A financial macro-network approach to climate policy evaluation. *Ecological Economics*, 149, 239–253.

FSB TCFD. (2018). *Recommendations of the Task Force on Climate-related Financial Disclosures*. *Final Report*.

UNFCCC (2016). Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Addendum. Part two: Action taken by the Conference of the Parties at its twenty-first session. (No. FCCC/CP/2015/10/Add.1). Paris: United Nations Framework Convention on Climate Change.

van der Ploeg, F. and Rezai, A., 2019. The agnostic's response to climate deniers: Price carbon!. *European Economic Review*, *111*, pp.70-84.