



Positive tipping points in a rapidly warming world

J David Tàbara¹, Niki Frantzeskaki², Katharina Hölscher², Simona Pedde³, Kasper Kok³, Francesco Lamperti^{4,5}, Jens H Christensen^{6,7}, Jill Jäger⁸ and Pam Berry⁹

The challenge of meeting the UNFCCC CoP21 goal of keeping global warming ‘well below 2 °C and to pursue efforts towards 1.5 °C’ (‘the 2–1.5 °C target’) calls for research efforts to better understand the opportunities and constraints for fundamental transformations in global systems dynamics which currently drive the unsustainable and inequitable use of the Earth’s resources. To this end, this research reviews and introduces the notion of *positive tipping points* as emergent properties of systems—including both human capacities and structural conditions — which would allow the fast deployment of evolutionary-like transformative solutions to successfully tackle the present socio-climate quandary. Our research provides a simple procedural synthesis to help identify and coordinate the required agents’ capacities to implement transformative solutions aligned with such climate goal in different contexts. Our research shows how to identify the required capacities, conditions and potential policy interventions which could eventually lead to the emergence of positive tipping points in various social–ecological systems to address the 2–1.5 °C policy target. Our insights are based on the participatory downscaling of global Shared Socio-economic Pathways (SSPs) to Europe, the formulation of pathways of solutions within these scenarios and the results from an agent-based economic modelling.

Addresses

¹ Institute of Environmental Sciences and Technology, Autonomous University of Barcelona, Campus UAB, 08193 Cerdanyola del Vallès (Barcelona), Catalonia, Spain

² Dutch Research Institute for Transitions, Faculty of Social Sciences, Erasmus University Rotterdam, The Netherlands

³ Soil Geography and Landscape Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands

⁴ Institute of Economics, Scuola Superiore Sant’Anna Piazza Martiri della Libertà 33, 56127 Pisa, Italy

⁵ Fondazione Eni Enrico Mattei, Corso Magenta 63, 20123 Milan, Italy

⁶ Danish Meteorological Institute, Lyngbyvej 100, DK-2100 Copenhagen O, Denmark

⁷ Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen O, Denmark

⁸ Independent, Vienna, Austria

⁹ Environmental Change Institute, University of Oxford, South Parks Road, Oxford, OX1 3QY, United Kingdom

Corresponding author: David Tàbara, J (joandavid.tabara@uab.cat)

Current Opinion in Environmental Sustainability 2018, 31:120–129

This review comes from a themed issue on **Sustainability governance and transformation**

Edited by **Bronwyn Hayward** and **Linda Sygna**

For a complete overview see the [Issue](#) and the [Editorial](#)

Available online 3rd March 2018

Received 01 June 2017; Revised 24 November 2017; Accepted 31 January 2018

<https://doi.org/10.1016/j.cosust.2018.01.012>

1877-3435/© 2018 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Introduction

The challenge of meeting the UNFCCC CoP21 goal of keeping global warming ‘well below 2 °C and to pursue efforts towards 1.5 °C’ (‘the 2–1.5 °C Paris target’) calls for the accelerated development of human capacities to implement transformative solutions in multiple contexts of action [1,2^{**},3]. In the present situation, it is essential not just to consider command-and-control policies for a ‘rapid decarbonisation’ [4] which would likely keep the root social causes, individual motives and incentive structures of excessive GHG emissions intact, but more importantly, and in terms of societal transformations, to identify the systemic conditions for a ‘rapid sustainabilisation’. This quest involves first of all, finding out more about which are the key dynamics that would eventually allow a fundamentally reversion of the current unsustainable and inequitable trends in the use of the Earth’s resources [5,6] and second, to explore the possibilities for individual and collective interventions in such dynamics given the limitations of existing governance arrangements.

This research has two main goals. On the one hand, it reviews the literature on tipping points from a sustainability science perspective and calls for research efforts to better characterize their use in policy making. Given our research focus, we concentrate on the notion of *positive tipping points*, understood as emergent properties derived from complex systems dynamics that allow rapid transformations in individual and collective practices so as to reach evolutionary-like solutions to the present socio-climate quandary. In this regard, we provide a simple

operational synthesis and framework aimed at identifying and supporting the building of agent capacities and system conditions conducive to such positive transformations [7]. Our approach is based on the acknowledgement of the structural uncertainty about when, where, how or even if such new fundamentally new system conditions, or positive tipping points, will emerge. It also recognizes that social–ecological dynamics are subject to multiple non-linear, irreversible and cumulative processes that cannot be anticipated. However, it is also based on the assumption that social–ecological systems can somehow be navigated intentionally to achieve certain desirable goals, targets or more broadly *visions*.

Assessing positive tipping points in a high-end climate World

Positive tipping points in social–ecological systems

Most research in sustainability science and integrated assessment has focused on examining the catastrophic, abrupt nature of tipping points in biophysical systems or the implications of the realization of such crises or of crossing such negative thresholds for policy and action [8–10,11*,12**,13,14]. However, and with few exceptions [15**,16], little attention has been paid so far to trying to identify and characterize the possible emergence of *positive tipping points* in social–ecological systems dynamics. In the context of climate change ‘beneficial social tipping points’ have been already referred to those which ‘increase societal resilience and reduce climate change damages via mitigation or adaptation, whereas harmful social tipping points are more likely to occur where there are low levels of societal resilience, under which societal risks increase because of failure to effectively adapt or mitigate’ [17**]. Such beneficial systemic changes may be derived from the synergetic, multiplicative learning feedback effects of deliberate implementation of transformative solutions developed in multiple contexts of action [18]. In this way, the articulation of learning feedbacks between multiple deliberate transformations at small system scales may be needed to achieve the long-term resilience at higher levels [19]. Addressing the question on how to achieve the Paris target precisely falls under these concerns [20]. It is neither possible to predict the exact moment, shape, dynamics or consequences of such required far-reaching changes in the configuration of global social–ecological systems nor if they will ever happen. However, and using an integrated research perspective, it may be possible to provide an operational framework to recognize the various conditions, capacities and concrete pathways of solutions, as well as the incentives [21], which could eventually lead in concrete contexts of action or subsystems to the emergence of positive tipping points. The later would increase our likelihood of successfully meeting the 2–1.5 °C Paris target.

Tipping points fundamentally and irreversibly change the structure and the intrinsic functioning of a given system of

reference. Some authors argue that early warnings and exceeding a threshold of concern about the acceptability of imminent occurrence of a tipping point may lead to ‘adaptation turning points’ in climate action [22] although this may be hard to put in practice. Some tipping points in certain systems may be unintentional and unexpected, others the result of deliberate actions. Trying deliberate or active transformations to achieve a fundamentally different kinds of systems may be necessary when the present institutions or systems’ goals become unattainable [19,23,24]. However, global social–ecological systems — for which global warming is but only a symptom and amplifier of its unsustainable dynamics, are constituted by many ‘systems of systems’ [25] each of which being determined by its own logics, complex dynamics and effects on other systems. For instance, a tipping point in the way that global communication systems operated occurred with the introduction of the internet, rather suddenly and unexpectedly and the ultimate effects of this transformation cannot yet be forecast; governance systems also follow their own rationales, mainly still under the nation-state interests and constraints and thus are largely resistant to change; the structure and the functioning of global energy and resource property systems are determined by price and market competition rules which in turn may be in conflict with other more traditional or local cultural systems in the use of natural resources; the building of institutional systems has also undergone tipping points in history, for example, when certain civil rights have been achieved, including the end of slavery, the end of child labour, the right of women to vote or to have access to education. The consolidation of the IPPC can be also seen as a tipping point in the development of science for policy to address the climate quandary, albeit with limited effects on global transformation [26]. Hence, both collective and individual social actions operate in multiple socio-cultural, technological, governance, bio-physical and knowledge systems which interact with many other systems at the same time and at many levels. Therefore, it is hard to think of the existence of a single transformative solution or a single tipping point in one single system that would lead to the achievement of the 2–1.5 °C target. Instead, multiple *positive tipping points* in multiple systems of action will be needed to achieve this aim.

There is little knowledge about which kinds of specific changes or *transformative solutions* are to be needed. Ultimately, such transformative solutions should be able to create new kinds of systemic conditions that eliminate the ultimate causes of the persistent problems. For this reason, we understand *positive tipping points* as emergent properties of systems that would allow the reaching of evolutionary-like transformative solutions to successfully tackle the present socio-climate quandary.

However, we admit that on the one hand, agents will only be able to act upon and apply transformative solutions to a

limited, albeit crucial, number of systems in which they operate — for example, recycling materials, preventing food waste, mobility, civic and political representation, etc. [27]. While on the other, particular transformative solutions that work in one context may not work in other contexts. A more nuanced narrative and interpretation of how different kinds of solutions can be linked or even supported through deliberate action-research to create multiplicative synergies and potentially induce *positive tipping points* to address the climate quandary is needed.

A procedural synthesis

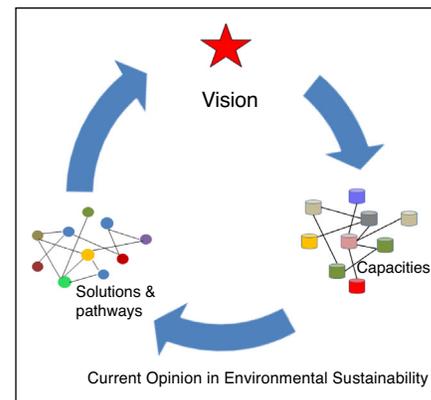
Given the large complexity and non-linearity in the dynamics of social–ecological systems, it is simply not possible to forecast the whole array of potentially transformative solutions that need to be implemented globally and which may contribute to the achievement of the 2–1.5 °C policy target. Instead, a more pragmatic approach can be formulated which focuses on identifying and characterizing the kinds of concrete and distributed capacities to implement these solutions. Required capacities will vary according to different people, needs and interests in their own contexts of action.

In this regard, a simple procedural framework can be developed linking desirable visions of the world, the building of agent capacities and systems of transformative solutions. Our perspective is based on the premise that transformations in social–ecological systems may be accelerated and purposefully brought about by social action. We make the case that in policy making a vision is a main driver of transformation [28–30,31**], rather than the impending awareness of a catastrophe [32], and that positive tipping points may be induced by the cascading, feedback and cumulative effects of multiple interlinked actions — or interlinked systems of transformative solutions — which eventually push a system towards a new desired configuration (Figure 1).¹⁰

A positive tipping point occurs when the original conditions of a system of reference are substantially and irreversibly transformed in a way that matches or exceeds a particular desired (normative), better-off configuration or *vision* (Figure 2). This moment is likely to happen fast only once agents have been able to build the required *capacities* to implement transformative solutions to do so. In this sense, tipping points will appear as emergent properties derived from the existing capacities which have been acquired when agents engage in applying their own systems of solutions to solve their problems according to their own needs and priorities (often in trial-and-error

¹⁰ This procedural synthesis is being used in the EU project GREEN-WIN (www.green-win-project.eu) to articulate a ‘Global Dialogue’ aimed at identifying and assessing a series of ongoing ‘win-win’ solutions (understood as class of transformative solutions which meet economic, sustainable development and climate goals) already being implemented around the World.

Figure 1



Linking agent capacities, pathways of solutions and visions to support systems' transformations.

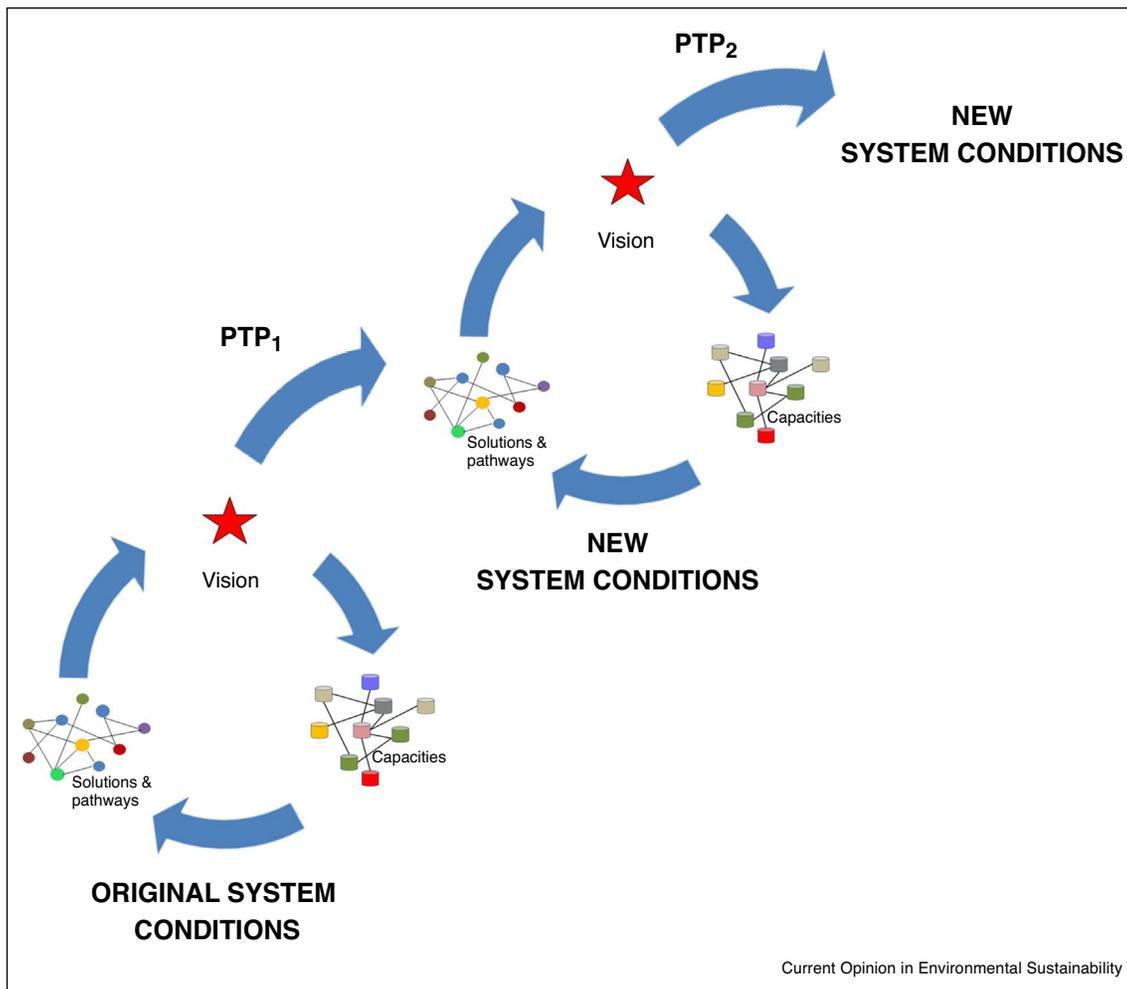
and learning mode) [33]. The implementation of transformative solutions may also lead to shifts in perception, the reconfiguration of social networks and of institutional arrangements [19]. Visions serve as a cognitive, emotional and normative reference for orienting and qualifying radical system changes as positive developments in a given system of reference. They also help to introduce the intersubjective nature of agents' motivations in collective action which lies at the base of social transformations [34], transformative science [35,36]; and in this way, visions play an important role in identifying the potential agency capacities to implement transformative solutions. However, visions are not static, and therefore they ought to be reframed as new conditions and ambitions change. A vision does not provide a single ‘end-point’ in systems trajectories, but only an open-ended desirable state that demands continuous improvement and reframing.

Co-producing pathways of transformative solutions in socio-economic scenarios

It is becoming increasingly common to co-produce in a participatory way pathways of solutions using exploratory scenarios to determine the opportunity spaces for systems' transformations [37–39]. Pathways are progressive courses of action for achieving strategic objectives, or more broadly to attain transformative visions, where short-term actions can pave the way for more medium and long-term actions. The pathways approach aids making sense of patterns of change and thinking of strategies and solutions to complex problems from an integrated and systemic perspective. Formulating pathways in concrete contexts helps to unveil climate actions that not only link adaptation and mitigation but also embrace broader transformative change [40–43].

The co-production of pathways can therefore help to identify and articulate integrated solutions and how they may unroll over time, for instance, in the context of

Figure 2



A positive tipping point (PTP) may be induced by boosting agents' capacities to implement pathways of solutions to achieve a transformative vision of the world.

different scenarios that provide opportunities and constraints for achieving the desired vision. Recently, a new set of global scenarios has been put forward by the modelling community [44–48]. The set includes the Shared Socioeconomic Pathways (SSPs) as five socio-economic scenarios¹¹ and the Representative Concentration Pathways (RCPs) which constitute emission scenarios that define global warming and thus climate change. By design, the development of the SSPs and RCPs was decoupled, allowing the matching of different socio-economic contexts with the same emission scenario. In particular SSPs are defined according to two key socio-economic challenges of High/Low Mitigation Challenges to High/Low Adaptation

¹¹ Having been defined as follows: SSP1 low challenges for adaptation and mitigation, SSP3 high challenges for mitigation and adaptation, SSP4 high for challenges adaptation, low for mitigation, SSP5 high challenges for mitigation, low for adaptation; while SSP2 moderate or 'middle of the road' challenges.

Challenges, but exclude Transformation as societal challenge independent from climate, which may be needed to address both mitigation and adaptation [36]. SSPs offer sets of baseline conditions and how they evolve differently over time, but since SSPs are exploratory they do not provide solutions to particular problems. They only describe the contexts from which the opportunity spaces for the development of different pathways of solutions may unfold.

However, there is still little research specifically aimed as downscaling these global scenarios and turn them into actionable strategies in particular contexts of action using participatory procedures. Within the EU project IMPRESSIONS¹², such an endeavour has been carried out at different spatial scales: from two municipalities in

¹² www.impressions-project.eu; see Berry, P.M., Betts, R.A., Harrison, P.A. and Sanchez-Arcilla, A. (Eds.) 2017. High-End Climate Change in Europe. Available at: <http://highendclimateresearch.eu/>.

Hungary to case studies in Scotland, Iberia, EU and Central Asia. The ultimate aim being to identify and assess potential pathways of solutions that could eventually be able to achieve a desired transformative vision of the world; or following the framework presented above, to 'flip' current system structures and dynamics into configurations attuned with the current climate and sustainability challenges.

In the European case study, four SSPs were co-developed based on online and workshops interaction with stakeholders.¹³ SSP2 was excluded from the participatory process given that the focus of the project was to identify the potential opportunities for transformation in a high-end climate change world (beyond 2 °C of global warming at the end of the century). In addition, the main discriminatory axes of 'challenges to mitigation/adaptation' were substituted by the axes of 'degree of social inequality/carbon intensity', with the aim of better capturing the essence of the key required changes in the socio-economic system while maintaining the link with greenhouse gas emissions. The newly adapted SSPs in IMPRESSIONS offered ways to think about transformations in various systems including energy, governance, socio-cultural, technological and economic systems and in this way to explore which structural conditions and capacities, could lead to positive fundamental systemic changes according to a normative vision of the future. While different SSPs tended to promote different kinds of solutions and pathways which emerged from the different available structural conditions, it was possible to identify some cross-scenario robust actions across all scenarios including concrete transformative solutions which participants believed to be 'game-changers' for moving towards the vision. In particular, and according to the stakeholders consulted the potential emergence of new systems' configurations or positive tipping points will be dependent on deploying transformative capacities of agents in systems such as:

- *Energy systems*: full switch to renewable energies and a move towards energy self-sufficient Europe in a way that makes full use of its context-dependent potential (e.g. solar energy in Southern Europe).
- *Governance*: civic participation if fully developed, with fair multi-level coordination and international cooperation in line with shared, integrated and long-term sustainability orientation.
- *Socio-cultural*: the European society widely adopts and normalises sustainability behaviours and is engaged in continuous learning and reflexivity.
-

¹³ This interaction started with a first expert workshop in January 2015, and two stakeholders workshops in February 2016 (23 stakeholders) and January 2017 (17 stakeholders) complemented with online interaction in the form of a questionnaire both before and between the workshops which focused on the design of the vision.

Technological systems: Green high-tech and low-tech infrastructure systems are fully integrated in Europe (e.g. household rainwater collection, integrated water sensitive infrastructure, green biodiversity corridors).

- *Resource systems*: full move towards a circular economy and towards organic agriculture.
- *Economy*: integrating ecosystem services, and a focus on quality of life and social wellbeing is integrated into the core economic activity.

In short, trying to deliberately achieve positive tipping points aligned with the 2–1.5 °C target and sustainability challenges would require the fast deployment of a mix of different types of transformative capacities to induce the synergetic, non-linear and cumulative effects which could be derived from the implementation of fundamental changes in the above systems. In addition, the articulation of learning feedbacks derived from the implementation of different actions and solutions is likely to be a core part of the required dynamics to build agents' capacities that would lead to a positive tipping point. This list, however, is not exhaustive and is only for illustrative purposes. Different contexts may yield alternative proposals or even consider other kinds of systems categorisation.¹⁴ In the scenario exercise, negative events and constraints for solution pathways were also identified, which included mostly the growing inequality, political de-stabilization matched with rampant environmental degradation which could make such positive transformation (in some systems) unattainable. Hence our results here only serve as an example of how the devising of a broad strategy, based on identifying feasible transformative solutions in concrete places could ultimately lead to a positive tipping point aligned with the pressing climate and sustainability goals.

Tippling points in the economy

A good part of the most promising and recent developments in the analysis of tipping points comes from economics [17**,49] — although markedly concentrated on negative tipping points which damage socio-economic and/or environmental conditions and general equilibrium effects (e.g. [50]) under single rational agent assumptions. Furthermore, standard cost-and-benefit analysis is likely to fail when uncertain regime-switches drive the behaviour of the system [51]. The effects and implications of negative tipping points are substantial when explored

¹⁴ For instance, there are other more radical transformations are being proposed in other circles, such as turning the functioning of the global economy and innovation systems from being based on ecosystems exploitation to be based on ecosystems restoration and reconnect it to the biosphere [21], creating a single global citizenship with equal citizens rights and responsibilities, applying fully key policy principles such as the polluter-pays and precautionary principles or simply phase out global fossil fuel extraction, the feasibility and acceptability of which and their contribution to flipping global systems dynamics to a different configuration aligned with the 2–1.5 °C could also be explored using this approach.

through models that do not endogenously account for threshold effects and tend to underestimate climate-related damages [52].

Instead, a relatively novel strand work focuses on modelling the economy, the environment, the climate and their multiple interactions as a large complex system [53,54], where both negative and positive tipping points are found as emergent properties [55,56]. This allows exploring agents' capacities to reach evolutionary-like solutions to the 1.5 °C challenge. Agent-based computational economics abandons dictates of agents' rationality and market equilibrium in favour of more realistic, yet computationally intense, representations of human behaviours and interactions [57] based on heterogeneous and bounded rational agents and networks. In such a context, both negative and positive tipping points emerge endogenously [58]. In IMPRESSIONS, Lamperti *et al.* [59] introduced the first agent-based integrated assessment DSK model and analyzed the impact of heterogeneous, individual-level climate damages on economic dynamics in line with the recent climate econometrics literature [60]. In a nutshell, the model is composed of two industrial sectors exchanging capital goods, an energy sector endowed with different energy technologies, a financial system providing credit to the economy and households that consume and provide labour force. Further, a dedicated climate module is added to the picture in order to track the dynamics of climate and environmental variables. A remarkable feature of the model is that it accounts for an ecosystem of heterogeneous agents (firms, households, energy plants and banks) that interact and realistically behave according to evolutionary routines. The model is calibrated in its baseline to a RCP 8.5 scenario relying on data from the World Bank and the RCP Database (version 2.0.5).

Large scale computational experiments show that cumulative climate damages might shift the system dynamics and trap the economy in a stagnant state characterized by absent economic growth and high unemployment, which cannot be exited even when emissions are dramatically reduced (Figure 3). The result emerges from the percolation of climate shocks in the network of agents that, at a certain point, are not able to react. In particular, firms' innovation-driven productivity gains are more than compensated by negative shocks, which increase defaults and exacerbate lack demand due to increased unemployment. Overall, these effects prevent economic recovery and switches of the engine of growth. Positive tipping points are also found: technological change and competition among different energy technologies produces different equilibria, characterized by energy mixes. Even though the system starts from a relatively high share of fossil-fuel-related energy production, a rapid transition towards a greener growth pattern, producing substantially higher growth and employment, is possible and synergetic with

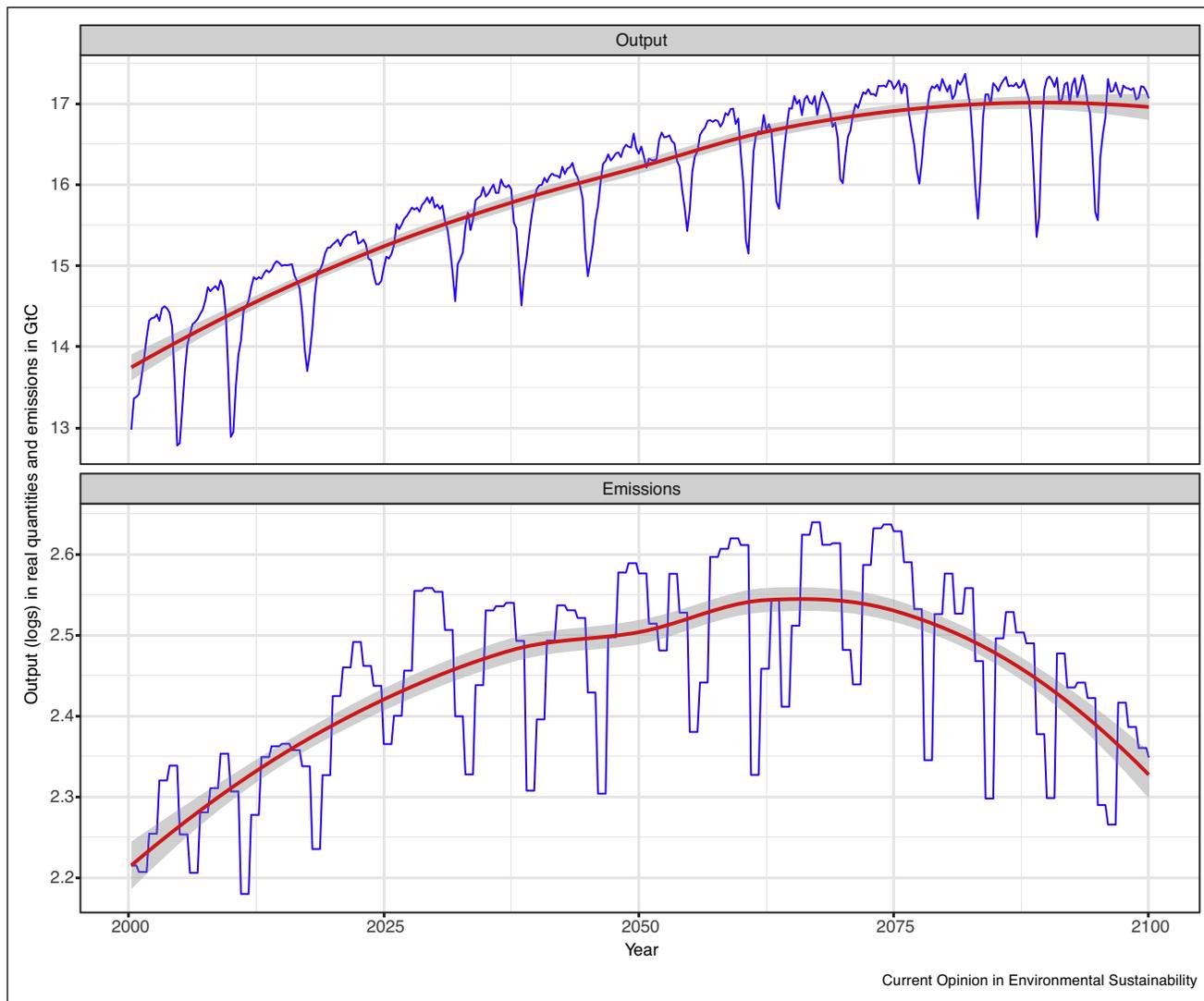
the effects of a large green Keynesian multiplier [61], derived from an active policy intervention. This may be exploited to construct pathways of solutions leading to positive tipping points (Figure 4). In our perspective, an endogenous and rapid transition to renewable energy sources constitute an example of positive tipping points, where economic agents autonomously moves away from carbon-intense technologies and self-organize in sustainable production systems. In particular, research and development (R&D) efforts are found to fast move away from fossil-fuel shocks due to increasing profitability of renewable technologies, whose development allows to slow emission growth and reduces future climate damage; such an effect further increases aggregate demand and sustain investment in green energy technologies thanks to the relatively lower unitary costs of production. The tipping element consists here in the relative competitiveness of green technologies, which self-sustain its growth pattern thanks to the aforementioned process, and help the economy rapidly abandon fossil-fuel-related R&D. However, our modelling results find that the likelihood of such tipping points is remarkably low and suggests that, timely and strong policy interventions are needed to increase the, otherwise extremely low, likelihood of crossing such positive thresholds [62].

Last but not least, multiple tipping points cannot be treated in isolation, as they are not independent: crossing one point deeply affects the likelihood of crossing another, creating either catastrophic or beneficial cascades. Regime shifts changing the trajectory of the economy also modify the selection of statistical equilibria the system might be attracted to in the future. This opens a wide range of risks, as the route from one regime to the other might not be smooth as mainstream neoclassical economics predicts. Coping with these risks also calls, at the very least, for timely and sharp policy interventions [63–65] and actions at multiple scales involving a variety of state and non-state actors, whose non-trivial governance requires appropriate tools accounting for the multi-layer networks linking different institutions.

Conclusion

The UNFCCC Paris goal of keeping global warming 'well below 2 °C and to pursue efforts towards 1.5 °C' cannot be considered a positive tipping point. Nor does it necessarily contain a transformative vision that could trigger the building of the necessary capacities to fundamentally change the current unsustainable dynamics of global systems accordingly [66]. Only when: (1) such a policy target can be aligned with a series of multiple visions, knowledge networks and sustainable practices already being developed around the World, and (2) the required capacities of agents have been effectively boosted so as to apply transformative solutions that meet their needs in concrete and many different contexts, may we have a better chance of moving closer to a positive

Figure 3



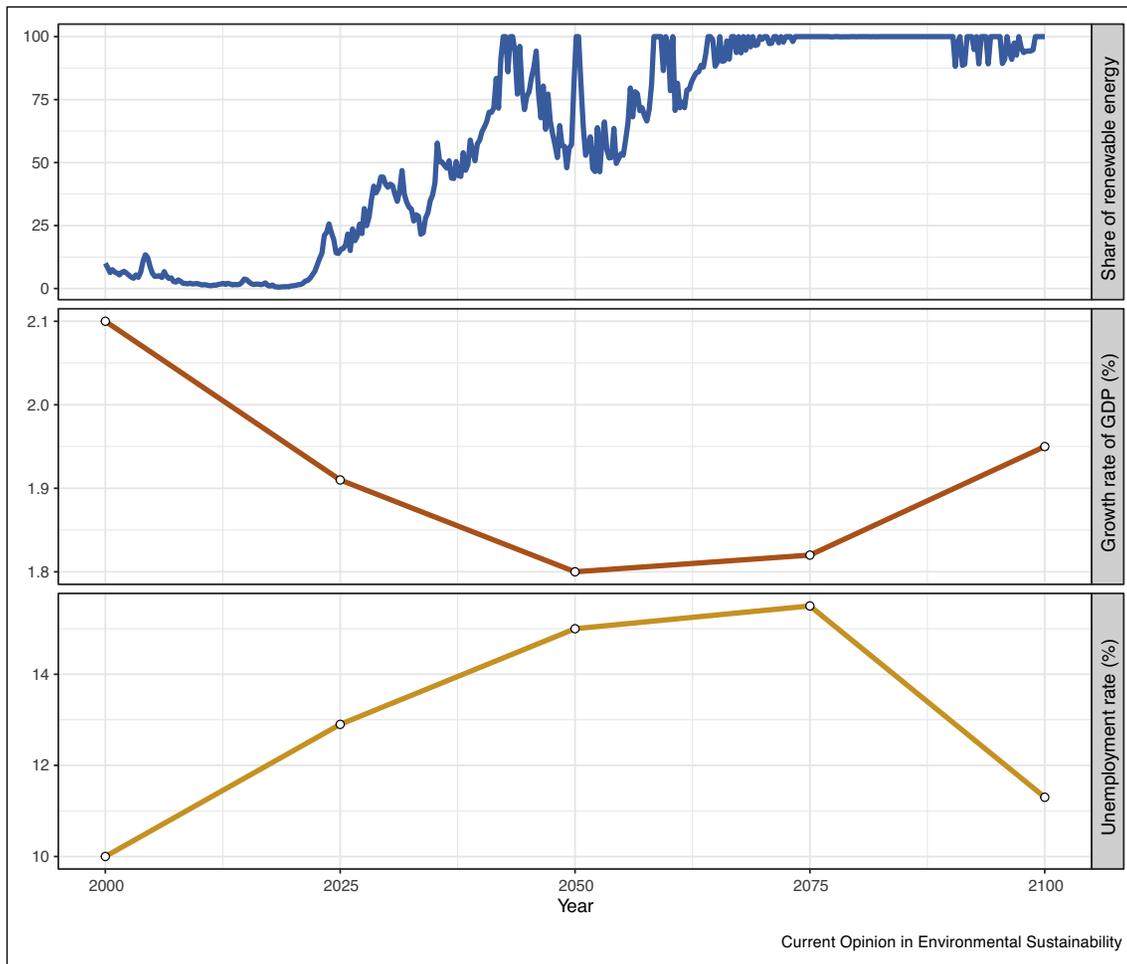
Example of negative economic tipping point from the DSK model. It represents the economy's shift towards a stagnating growth pattern which is not exited when emissions are reduced.

tipping point in collective action whereby present global dynamics are fundamentally modified and address the climate challenge in an equitable and sustainable way.

Certainly, in a world constituted by a closely interconnected 'systems of systems', multiple positive tipping points are needed to address the 2–1.5 °C target. At present, and given their non-linear, cumulative and complex dynamics it is not possible to anticipate when, how, where or even if such positive tipping points will occur. However, what is possible, at least from an integrated assessment perspective, is to identify and appraise the kinds of specific *capacities* which could help to implement concrete *transformative solutions* in many different systems of action and to do so according to the needs and priorities of different kinds of groups and people.

In particular, the required capacities that would lead to positive tipping points in system dynamics will vary according to future social–ecological conditions in which humans will live in the future. Such conditions, and the potential policy interventions to alter them, can be represented and assessed using various tools and methods. In this research, we used the results of the downscaling of the Shared Socio-economic Pathways (SSPs) and the co-production of strategic pathways in Europe together with the outputs from an agent-based modelling exercise. These results showed that some pathways of transformative solutions which may occur at certain moments in time may drive certain systems closer (or further away) from their desired positive systemic transformation. That is, there is not one single solution or pathway of solutions to the 2–1.5 °C target: but thousands of them of very

Figure 4



Example of positive economic tipping point from the DSK model. It represents an endogenous transition towards renewable energy sources boosting economic performances.

different kinds. The ultimate shape and content of these solutions will depend on the many systems of reference in which agents operate around the world; and if these are aligned with their own transformative visions for a better life, there may be a greater chance to develop multiplicative synergies and multiple learning feedbacks amongst them, ultimately leading to global positive tipping point in way global systems operate.

Conflict of interest statement

Nothing declared.

Acknowledgements

The research has received funding from the EU projects IMPRESSIONS- Impacts and Risks from High-End Scenarios: Strategies for Innovative Solutions (www.impressions-project.eu; EC FP7/2007-2013 grant no. 603416) and GREEN-WIN – Green Growth and Win-Win Strategies for Sustainable Climate Action (<http://green-win-project.eu/>; EC Horizon grant

no. 642018). We would like to thank Andrea Roventini and Diana Mangalagiu for their input and the very insightful comments received from three anonymous reviewers to an earlier manuscript.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- of outstanding interest

1. Westley FR, Tjornbo O, Schultz L, Olsson P, Folke C, Crona B, Bodin O: **A theory of transformative agency in linked social-ecological systems.** *Ecol Soc* 2013, **18**:27.
2. Westley FR, McGowan KA, Antadze N, Blacklock J, Tjornbo O: **How game changers catalyzed, disrupted, and incentivized social innovation: three historical cases of nature conservation, assimilation, and women's rights.** *Ecol Soc* 2016, **21**:13.

This paper positions game changes as macro-phenomena in relation to social innovation. Three examples of game changers are analysed to

discern how they create opportunity contexts for social innovations to emerge and mature.

3. Ziervogel G, Cowen A, Ziniades J: **Moving from adaptive to transformative capacity: building foundations for inclusive, thriving and regenerative urban settlements.** *Sustainability* 2016, **8**:955.
4. Rockström J, Gaffney O, Rogelj J, Meinshausen M, Nakicenovic N, Schellnhuber NHJ: **A roadmap for rapid decarbonization.** *Science* 2017, **355**:1269-1271.
5. Steffen W, Broadgate W, Deutsch L, Gaffney O, Ludwidge C: **The trajectory of the anthropocene: the great acceleration.** *Anthropocene Rev* 2015, **2**:81-98.
6. Chapin FS, Carpenter SR, Kofinas GP, Folke C, Abel N, Clark WC, Olsson P, Stafford Smith DM, Walker BH *et al.*: **Ecosystem stewardship: sustainability strategies for a rapidly changing planet.** *Trends Ecol Evol* 2010, **25**:241-249.
7. Gillard R, Gouldson A, Paavola J, van Alstine J: **Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation.** *WIREs: Clim Change* 2016, **7**:251-265.

This paper reviews the contribution of socio-technical transitions and social-ecological resilience approaches to conceptualizing climate mitigation and adaptation. Emphasis is given to the role of agency in enacting social change to move away from actor-empty systemic perspective and highlight questions of power and politics.

8. Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ: **Tipping elements in the Earth's climate system.** *Proc Natl Acad Sci U S A* 2008, **105**:1786-1793.
9. Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA *et al.*: **Planetary boundaries: guiding human development on a changing planet.** *Science* 2015, **347**:6223.
10. Russill C: **Climate change tipping points: origins, precursors, and debates.** *Wiley Interdiscipl Rev Clim Change* 2015, **6**:1757-7780.
11. Lorbach D, Avelino F, Haxeltine A, Wittmayer JM, O'Riordan T, Weaver P, Kemp R: **The economic crisis as a game changer? Exploring the role of social construction in sustainability transitions.** *Ecol Soc* 2016, **21**:15.

This paper looks at the economic crisis as an example of a game changer that is a symptom of long-term societal changes and that can accelerate or hamper social and political reform as well as innovative practices.

12. Nuttall M: **Tipping points and the human world. Living with change and thinking about the future.** *Ambio* 2011, **41**:96-105. A lucid anthropologist and sociological critique of the catastrophic, fatalistic, terror-inducing discourse of tipping point as deployed by natural scientists and positive approaches which is deemed as 'far too simplistic'. Instead the author advocates for anticipation and for focusing on a more nuanced understanding meaning construction in the diversity of local contexts to think about precaution and preparedness to climate change.
13. Brondizio ES, O'Brien K, Bai X, Biermann F, Steffen W, Berkhout F, Cudennec C, Lemos MC, Wolfe A, Palma-Oliveira J, Chen C-TA: **Re-conceptualizing the Anthropocene: a call for collaboration.** *Glob Environ Change* 2016, **39**:318-327.
14. Galaz V, Österblom H, Bodin Ö, Crona B: **Global networks and global change-induced tipping points.** *Int Environ Agreem Polit Law Econ* 2016, **16**:189-221.
15. Totten MP: **GreenATP. APPortunities to catalyse local to global positive tipping points through collaborative innovation networks.** *WIREs: Energy Environ* 2012, **1**:98-113. This paper introduces the concept of Positive Tipping Points and analyses the positive transformation role of web-based Collaboration Innovation Networks (COINs) enabling the acceleration of multiple-benefit innovations to solve problems confronting humanity.
16. Jordan TE: **Recommendations for interdisciplinary study of tipping points in natural and social systems.** *Eos* 2010, **91**:143-144.
17. Kopp RE, Shwom RL, Wagner G, Yuan J: **Tipping elements and climate-economic shocks: pathways toward integrated assessment.** *Earth's Future* 2016:346-372.

A very comprehensive and useful review which addresses both tipping points in biophysical systems as in socio-economic systems and which covers both negative and beneficial tipping points.

18. Moore ML, Tjornbo O, Enfors E, Knapp C, Hodobod J, Baggio JA, Norström A, Olsson P, Biggs D: **Studying the complexity of change: toward an analytical framework for understanding deliberate social-ecological transformations.** *Ecol Soc* 2014, **19**:54.
19. Folke C, Carpenter SR, Walker B, Scheffer M, Chapin T, Rockström J: **Resilience thinking: integrating resilience, adaptability and transformability.** *Ecol Soc* 2010, **15**:20.
20. Lee H: **Turning the focus to solutions.** *Science* 2015, **350**:1007.
21. Westley F, Olsson P, Folke C, Homer-Dixon T, Vredenburg H, Lorbach D, Thompson J, Nilsson M, Lambin E, Sendzimir J, Banerjee B, Galaz V, van der Leeuw S: **Tipping toward sustainability: emerging pathways of transformation.** *Ambio* 2011, **40**:762-780.
22. Werners SE, Pfenninger S, van Slobbe E, Hassnoot M, Kwakkel JH, Swart RJ: **Thresholds, tipping and turning points for sustainability under climate change.** *Curr Opin Environ Sustain* 2013, **5**:334-340.
23. Walker B, Holling CS, Carpenter SR, Kinzig A: **Resilience, adaptability and transformability in social-ecological systems.** *Ecol Soc* 2004, **9**:5.
24. O'Riordan T, Lenton TM: **Tackling tipping points.** *Brit Acad Rev* 2011, **18**:21-27.
25. Jaeger C, Jansson P, van der Leeuw S, Resch M, Tåbara JD, Dum R (Eds): *Global System Science Orientation Paper*. Background Material and Synthesis; 2013 <http://www.gsdp.eu/about/global-systems-science/>.
26. Tåbara JD, Lera St, Clair A, Hermansen EAT: **Transforming communication and knowledge production processes to address high-end climate change.** *Environ Sci Pol* 2017, **70**:31-37.
27. O'Brien K: **Political agency: the key to tackling climate change.** *Science* 2015, **350**:1170-1171.
28. Andreescu L, Gheorghiu R, Zulean M, Curaj A: **Understanding normative foresight outcomes: scenario development and the 'veil of ignorance' effect.** *Technol Forecast Soc Change* 2013, **80**:711-722.
29. Miller CA, O'Leary J, Graffy E, Stechel EB, Dirks G: **Narrative futures and the governance of energy transitions.** *Futures* 2015, **70**:65-74.
30. Wiek A, Iwaniec D: **Quality criteria for visions and visioning in sustainability science.** *Sustain Sci* 2014, **9**:497-512.
31. Bai X, van der Leeuw S, O'Brien K, Berkhout F, Biermann F, Brondizio ES, Cudennec C, Dearing J, Duraiappah A, Glaser M, Revkin A, Steffen W, Syvitski J: **Plausible and desirable futures in the Anthropocene: a new research agenda.** *Glob Environ Change* 2016, **39**:351-362. This paper re-focuses the debate about the Anthropocene on the future, arguing for the need to understand societal goals, major trends and underlying dynamics to focus on opportunities for realising desirable and plausible futures.
32. Lenton T: **Tipping climate cooperation.** *Nat Climate Change* 2014, **4**:14-15.
33. Tåbara JD, Chabay I: **Coupling human information and knowledge systems with social-ecological systems change. reframing research, education and policy for sustainability.** *Environ Sci Pol* 2013, **28**:71-81.
34. O'Brien K: **Climate change and social transformations: is it time for a quantum leap?** *Wiley Interdiscipl Rev: Clim Change* 2016, **7**:618-626.
35. Tschakert P, Tuana N, Westkog H, Koelle B, Afrika A: **T-Change: the role of values and visioning in transformative science.** *Curr Opin Environ Sustain* 2016, **20**:21-25.
36. Tåbara JD, Jäger J, Mangalagiu D, Grasso M: **Defining Transformative Climate Science in the context of high-end**

- climate change.** *Reg Environ Change* 2018 <http://dx.doi.org/10.1007/s10113-018-1288-8>. IMPRESSIONS project Special Issue.
37. Abel NR, Wise M, Colloff MJ, Walker BH, Butler JRA, Ryan P, Norman C, Langston A, Anderies JM, Gorddard R, Dunlop M, O'Connell D: **Building resilient pathways to transformation when "no one is in charge": insights from Australia's Murray-Darling Basin.** *Ecol Soc* 2016, **21**:23.
 38. Wise R, Fazey I, Stafford Smith M, Park S, Eakin H, Archer Van Garderen E, Campbell B: **Reconceptualising adaptation to climate change as part of pathways of change and response.** *Glob Environ Change* 2014, **28**:325-336.
 39. Kok K, van Vliet M, Bärlund I, Dubel A, Sendzimir J: **Combining participative backcasting and explorative scenario development: experiences from the SCENES project.** *Technol Forecast Soc Change* 2011, **78**:835-851.
 40. Rosenbloom D: **Pathways: an emerging concept for the theory and governance of low-carbon transitions.** *Glob Environ Change* 2017, **43**:37-50.
 41. Luederitz C, Abson DJ, Audet R, Lang DJ: **Many pathways toward sustainability: not conflict but co-learning between transition narratives.** *Sustain Sci* 2017, **12**:393-407.
 42. Burch A, Shaw A, Dale A, Robinson J: **Triggering transformative change: a development path approach to climate change response in communities.** *Clim Pol* 2014, **14**:467-487.
 43. Patterson J, Schulz K, Vervoort J, van der Hel S, Widerberg O, Adler C, Hurlbert M, Anderton K, Sethi M, Barau A: **Exploring the governance and politics of transformations towards sustainability.** *Environ Innov Soc Transit* 2017, **24**:1-16.
 44. Moss RH, Edomons JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T *et al.*: **The next generation of scenarios for climate change research and assessment.** *Nature* 2010, **463**:747-756.
 45. O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, Levy M, Solecki W: **The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century.** *Glob Environ Change* 2015, **42**:169-180.
 46. van Vuuren D, Krieger E, O'Neill BC, Ebi KL, Riahi K, Carter TR, Edmonds J, Hallegatte S, Kram T, Mathur R, Winkler H: **A new scenario framework for Climate Change Research: scenario matrix architecture.** *Clim Change* 2014, **122**:373-386.
 47. Ebi KL, Hallegatte S, Kram T, Arnell NW, Carter TR, Edmonds J, Kriegler E, Mathur R, O'Neill BC, Riahi K, Winkler H, Van Vuuren DP, Zwickel T: **A new scenario framework for climate change research: background, process, and future directions.** *Clim Change* 2014, **122**:363-372.
 48. Kriegler E, O'Neill BC, Hallegatte S, Kram T, Lempert RJ, Moss RH, Wilbanks T: **The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways.** *Glob Environ Change* 2012, **22**:807-822.
 49. de Zeeuw A, Li CZ: **The economics of tipping points.** *Environ Resour Econ* 2016:513-517.
 50. Lemoine D, Traeger CP: **Economics of tipping the climate dominoes.** *Nat Clim Change* 2016, **6**:514-519.
 51. Cai Y, Judd KL, Lenton TM, Lontzek TS, Narita D: **Environmental tipping points significantly affect the cost-benefit assessment of climate policies.** *Proc Natl Aca Sci U S A* 2015, **112**:4606-4611.
 52. Stern N: **Economics: current climate models are grossly misleading.** *Nature* 2016, **530**:407-409.
 53. Balint T, Lamperti F, Mandel A, Napoletano M, Roventini A, Sapio A: **Complexity and the economics of climate change: a survey and a look forward.** *Ecol Econ* 2017. (in press).
 54. Lamperti F, Mandel A, Napoletano M, Roventini A, Sapio A, Balint T, Khorenzhenko I: **Towards agent-based integrated assessment models: examples, challenges and future developments.** *Reg Environ Change* 2018. IMPRESSIONS Special Issue. Forthcoming.
 55. Tàbara JD, Mangalagiu D, Kupers R, Jaeger CC, Mandel A, Paroussos L: **Transformative targets in sustainability policy-making: the case of the 30% EU mitigation goal.** *J Environ Plan Manage* 2013, **56**:1180-1191.
 56. Gualdi S, Tarzia M, Zamponi F, Bouchaud JP: **Tipping points in macroeconomic agent-based models.** *J Econ Dyn Control* 2015, **50**:29-61.
 57. Tesfatsion L, Judd KL: *Handbook of Computational Economics: Agent-based Computational Economics*. Elsevier; 2006.
 58. Student J, Amelung B, Lamers M: **Towards a tipping point? Exploring the capacity to self-regulate Antarctic tourism using agent-based modeling.** *J Sustain Tour* 2016, **24**:412-429.
 59. Lamperti F, Dosi G, Napoletano M, Roventini A, Sapio A: *Faraway, so close: coupled climate and economic dynamics in an agent-based integrated assessment model.* LEM working papers. 2017. 2017/12.
 60. Carleton TA, Hsiang SM: **Social and economic impacts of climate.** *Science* 2016, **353**.
 61. Zenghelis D: **A strategy for restoring confidence and economic growth through green investment and innovation.** *Policy Brief* 2012.
 62. Lamperti F, Dosi G, Napoletano M, Roventini A, Sapio A: *And then He Was a She: Climate Change and Green Transition in an Agent-Based Integrated Assessment Model, 2018.* LEM Working Papers. 2018. <http://www.lem.sssup.it/wplem.html>.
 63. Lontzek TS, Cai Y, Judd KL, Lenton TM: **Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy.** *Nat Clim Change* 2015, **5**:441-444.
 64. Cai Y, Lenton TM, Lontzek TS: **Risk of multiple interacting tipping points should encourage rapid CO₂ emission reduction.** *Nat Clim Change* 2016, **6**:520-525.
 65. van der Ploeg F: **Climate change economics: reacting to multiple tipping points.** *Nat Clim Change* 2016, **6**:442-443.
 66. Hermville L: **Climate change as transformation challenge. A new climate policy paradigm?** *GAIA* 2016, **25**:19-22.