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Cross-system interactions for positive tipping cascades

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Abstract. Positive tipping points are promising leverage points in social systems for accelerated progress towards climate and sustainability targets. Besides their impact in specific social systems such as energy, food, or social norms and values, positive tipping dynamics may in some cases spread across different systems, amplifying the impact of tipping interventions. However, the cross-system interactions that can create such tipping cascades are sparsely examined. Here, we review interactions across sociotechnical, socioecological, socioeconomic, and sociopolitical systems that can lead to tipping cascades based on the emerging and relevant past evidence. We show that there are several feedback mechanisms where a strategic input can trigger secondary impacts for a disproportionately large positive response, and various agents that can trigger such cascades. This review of cross-system interactions facilitates the quantification and analysis of positive tipping cascades in future studies.

1 Introduction

A tipping point refers to a critical threshold in complex systems beyond which self-propelling feedback leads to a fundamentally different system state (Lenton, 2020). The concept of positive (or social) tipping has gained wide attention recently to accelerate climate change mitigation and adaptation. Conceptually, tipping dynamics are characterized by alternative stable states, non-linearity, underlying positive feedback loops, and limited reversibility, and "positive" tipping is specifically marked by desirability and intentionality in advancing decarbonization and sustainability (Milkoreit, 2022). Due to the promise of rapid change once the positive feedback mechanisms are triggered, such tipping points are considered high-leverage opportunities to use limited policy resources most efficiently for rapid decarbonization (Otto et al., 2020; Tàbara et al., 2018) and to counteract the risk of non-linear climate change due to climate tipping points (Armstrong McKay et al., 2022) that may be observed by the end-of-century unless climate targets are reached.

Positive tipping dynamics have been, or can potentially be, observed in various sociotechnical and environmental systems. For instance, subsidy programmes and decentralized production can trigger rapid decarbonization in energy production and storage, and divestment movement from fossil fuels can rapidly increase investors' perceived risk of carbon-intensive assets in the financial system (Otto et al., 2020). If there are strong interconnections between these systems, a positive tipping intervention can lead to a sequence of secondary impacts across different systems (Sharpe and Lenton, 2021), such as energy, finance, and policy, and across different scales, such as individual, national, and international. These secondary impacts, called cascades, result in a much larger eventual impact. As positive tipping in a specific system, positive tipping cascades are characterized by desirability and intentionality towards decarbonization and sustainability; hence, the existing cross-system interconnections that enable, facilitate, or strengthen climate change mitigation, adaptation, and sustainability efforts are considered a positive tipping cascade. Such cross-system interactions also create cascading feedback mechanisms that can further reinforce the positive feedbacks within those systems and accelerate the tipping dynamics or vice versa. Therefore, identifying and managing such cascades is necessary to accelerate tipping dynamics and boost the effectiveness of positive tipping interventions towards rapid decarbonization.

An archetypical example of cross-system cascades that led to rapid socioeconomic change is the Industrial Revolution in Britain ca. 1760–1840 (Lenton and Scheffer, 2023). High wages spurred innovation in the substitution of energy for labour, and innovation in cotton manufacturing triggered much wider applications of machines and the new modes of production. Increasing energy demand led to innovation in resource extraction, in the energy efficiency of steam engines, and in a transport network to move heavy materials (e.g. coal, iron) around. That transport network in turn expanded markets for both heavy and pre-existing lighter goods. Increasing demand for such goods from a growing middle class drove further investment in innovation, increasing productivity and maintaining economic growth. Similar cascade dynamics can facilitate a rapid transformation in the current state of the world to achieve climate and sustainability targets. Despite this promise of positive tipping cascades, however, their analysis in the emerging positive tipping literature is limited. A recent review of the positive (or social) tipping literature shows that almost two-thirds of the emerging literature focuses on a single system, rather than multiple systems and their interactions (Eker et al., 2024). Therefore, it is worthwhile to address this research gap and identify cross-system interactions that can potentially create positive tipping cascades.

Here, we describe key examples of cascading effects and feedback loops across various sociotechnical (e.g. energy, transport), social-ecological (e.g. agriculture), and sociopolitical systems. Having a dynamic systems perspective, we delineate the feedback mechanisms between these systems that can amplify the positive tipping dynamics. Besides a better understanding of the state and potential of positive tipping, we aim to shed light on how such tipping dynamics can be triggered by civil society and the private sector, creating the constituency for government-led interventions, and how they can be managed by limiting negative cascades and inducing positive ones. We acknowledge that not every cross-system interaction leads to a cascading effect for positive tipping, and many of those might be preventing or dampening the change towards rapid climate action and sustainability. While considering such dampening effects is of utmost importance to assess the plausible potential of positive tipping, in this paper we focus only on the cross-system feedbacks that can amplify the positive tipping dynamics. We note that the examples we present here do not constitute the whole range of possible positive tipping cascades, especially from the hard-to-abate sectors such as heavy industry, and do not necessarily include cross-system connections that do not exist yet. Therefore, in Sect. 3.2 we briefly outline a future research agenda that can systematically identify further positive tipping cascades.

In the remainder of this paper, we provide an overview of the positive tipping cascades and review the key examples in Sect. 2. In Sect. 3, we discuss how the promising potential of these cascades can be harnessed and triggered by different agents and how research can support this. We conclude with a discussion on the normative recommendations for tipping social systems in Sect. 4.

2 Cross-system interactions leading to cascades

The cross-system interactions within sociotechnical, socioecological, and sociopolitical systems can lead to positive tipping cascades that can amplify the impact of tipping interventions in each system. Historically, interacting political, technological, and behavioural tipping elements such as the Montreal Protocol, development of non-CFC substitutes, and public concerns over UV radiation and skin cancer led to a rapid phasing out of ozone-depleting chemicals (Stadelmann-Steffen et al., 2021). Similarly, zero-emission vehicle (ZEV) mandates are a strong leverage point due to cascading effects across systems and scales. As policies require manufacturers to ensure ZEVs account for rising proportion of their car sales, they overcome a constraint on supply in the transport sector, facilitate decarbonization in the energy sector through innovation, and raise the demand from society. Versions of this policy have proved highly effective in California, China, and the Canadian provinces of Quebec and British Columbia, combined with installation of charging stations. These ZEV policies in a few pioneering countries have also been shown to accelerate the transition across countries and sectors on a global scale (Sharpe and Lenton, 2021; Bernstein and Hoffmann, 2019). In the future, as the simulation results of Moore et al. (2022) show, cascading positive feedbacks through individual action, social conformity, climate policy, and technological learning could tip the global carbon emissions towards a rapid decline.

Below, we describe the interactions within and between the sociotechnical (energy, transport), socioecological (food and land use), and sociopolitical (society and policy, including finance) systems that could amplify decarbonization and sustainability action in near future. Figure 1 depicts those interactions and the main mechanisms facilitating them, which we discuss in detail below and highlight the role and ability of various agents in triggering cascades.

2.1 Cascading effects in sociotechnical systems

Across sociotechnical systems, cascading effects can occur when one sector drives the cost of a shared technology down,

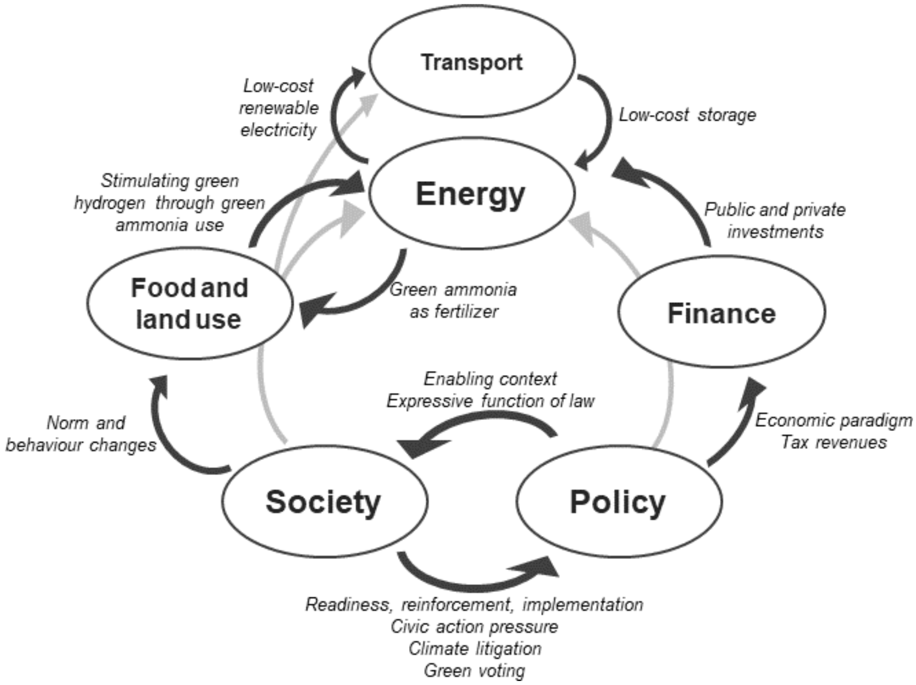

Figure 1. Overview of the cross-system interactions that can create positive tipping cascades. Arrows refer to the cross-system interactions, and the main mechanisms of these interactions are annotated near the arrows.

or when the output of one sector provides a low-cost input to others. Electricity is a general purpose technology, and with renewable energy becoming the cheapest source of electricity generation (Way et al., 2022), there is the potential for economy-wide cascading consequences across the electricity sector, mobility, and heating. Low-cost renewable electricity combined with cheaper and longer-duration battery storage is making direct electrification highly attractive in some sectors of the economy (e.g. light-road transport) and more feasible in others (e.g. heavy-duty transport, short-haul shipping, and aviation). Specifically, passenger electric vehicles (EVs) represent the majority of projected demand for batteries, with estimates suggesting that they will account for ∼70 % of total installed battery capacity by 2030. At the same time, wider deployment of EVs reduces the battery costs, further reducing the renewables' storage costs in the energy sector. Meldrum et al. (2023) highlight that boosting EV adoption to 60 % of total global passenger vehicle sales by 2030 would increase the total volume of battery production by 10 times from current levels, while a continuation of the currently announced projects would increase the battery production capacity only by 4 times from the current levels (IEA, 2023). Given current learning rates, this could drive a 60 % reduction in battery costs by 2030. As battery costs account for ∼30 % of the total cost of renewable power, a 60 % reduction in them will bring forward cost parity points of new solar and wind energy, including storage, with new or existing gas (or coal) power generation. Figure 2 illustrates this reinforcing (positive) feedback mechanism between the EV deployment, renewable energy, and storage costs.

Cheaper batteries provide cost-effective electricity storage also to balance intermittent renewable energy supply and demand, encouraging homeowners to install batteries that charge at low rates during the night and provide power at times of peak demand during the day. Furthermore, declining costs of renewables boosts the use of heat pumps in residential heating with higher demand for renewables in return (Meldrum et al., 2023), further reducing the renewables' cost due to learning and economies of scale. Figure 2 depicts this positive feedback loop of residential renewable energy consumption. In the mobility sector, cheaper and better-performing batteries, as well as the advancing electric drivetrain technology, are increasing the competitiveness of electric trucks, bringing forward the point where they outcompete petrol or diesel trucks, forming another positive feedback mechanism between the transport and energy sectors. Linked with advances in digitalization, this spurs decentralization of electricity generation.

The impact of cheaper electrolysers and renewable energy goes beyond the electricity sector, mobility, and home energy and creates new avenues for industries to decarbonize using green hydrogen and its derivatives. For instance, green ammonia (produced from hydrogen with renewable energy) can be used for agricultural fertilizers, shipping fuel, and synthetic jet fuel in aviation, which are hard-to-abate industries. It can also be a storage option to facilitate load balancing in renewable electricity systems (Edmonds et al., 2022;

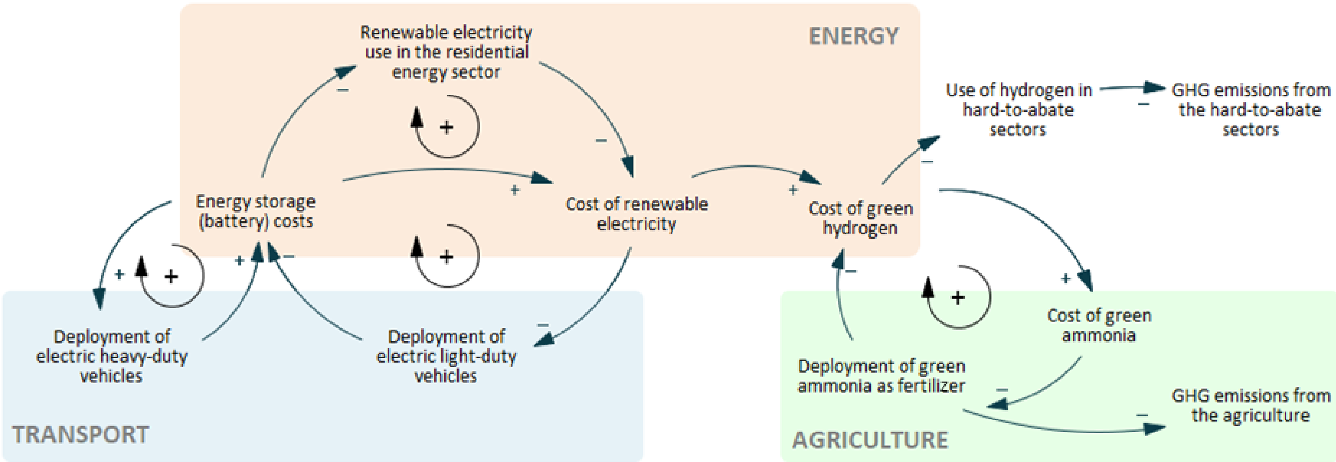

Figure 2. Interaction examples between the energy, transport, and agricultural systems. Using the notation of causal loop diagramming, a positive link from variable A to B means that a change in A leads to a change B in the same direction, whereas a negative link implies a change in the opposite direction. A circular arrow with a positive mark in the middle refers to a positive feedback loop.

Bouaboula et al., 2023). Green ammonia is already cost competitive in fertilizer production, thanks also to its low transport costs either through pipelines or shipping (IEA, 2019). With economies of scale and learning, progress in green ammonia use for fertilizers could bring down the cost of green hydrogen for use in several other sectors. For example, implementing a 25 % green ammonia blending mandate in fertilizer manufacturing could create demand for almost 100 GW of hydrogen electrolysers, which would reduce capital costs by ∼70 % given current learning rates. This could unlock USD 1.5 kg^{-1} green hydrogen costs if accompanied by continued falls in the cost of clean electricity, helping to close the gap to cost parity or increase the economic viability of zero-emission solutions in other sectors including steel production and shipping. Figure 2 illustrates this positive feedback loop of cost reduction in green hydrogen through its use in agriculture and the wider impacts on hard-to-abate sectors.

The effect of society on the energy and transport systems through norm and behaviour changes is also expected to be significant, even though it is not visualized in Fig. 2 for simplicity. Demand-side mitigation solutions, that is, changes in consumers' technology choices, consumption, behaviour, and lifestyles, could provide reductions of up to 78 %, 62 %, and 41 % of the expected greenhouse gas (GHG) emissions by 2050 in the residential energy, transport, and industry sectors, respectively (Creutzig et al., 2022). In other words, social and behavioural changes are cross-cutting enablers of positive tipping dynamics in various sociotechnical and socioeconomic systems (Spaiser et al., 2023).

2.2 Cascading effects in socioecological systems

Food and land use is one of the key systems that can create tipping dynamics for accelerated decarbonization. Self-reinforcing feedback loops such as increasing returns and technological reinforcement can progressively change an inadequate food system into a more sustainable one (Lenton et al., 2022; Fesenfeld et al., 2022; FOLU, 2021).

Social change in the form of widespread behaviour changes towards lower waste, sustainable diets, and diversified protein sources can not only reduce the GHG emissions of the agriculture sector but also create synergies for achieving multiple sustainable development goals, such as alleviating hunger, improving public health, averting biodiversity loss, and reducing the intensity of trade-offs between them (van Vuuren et al., 2018; Obersteiner et al., 2016; Leclère et al., 2020).

As illustrated in Fig. 3, dietary behaviour changes towards sustainable food consumption reduce agricultural land needs and hence the land pressure (Springmann et al., 2018). As the land pressure declines, fertilizer consumption is expected to decline because the increasing need for cropland and grassland to supply the required food to a growing population has been the main driver of increased fertilizer use in agriculture in the last 5 decades (Lu and Tian, 2017). Similarly, a declining land pressure is expected to increase the adoption of diversified and regenerative farming practices (Gosnell et al., 2019), as well as ecological restoration and associated carbon sequestration, leading to more rapid decarbonization in agriculture. In climate-vulnerable, low-income economies, these feedbacks can also drive diversification of livelihoods, new economic opportunities, and other social benefits.

Social norms have been repeatedly shown to be a key driver of widespread dietary changes in model-based (Elliot, 2022; Eker et al., 2019) and experimental studies (Mollen et al., 2013; Sparkman and Walton, 2017). As more people adopt sustainable diets, the visibility of it will lead to a stronger perception of the sustainability norms, leading to

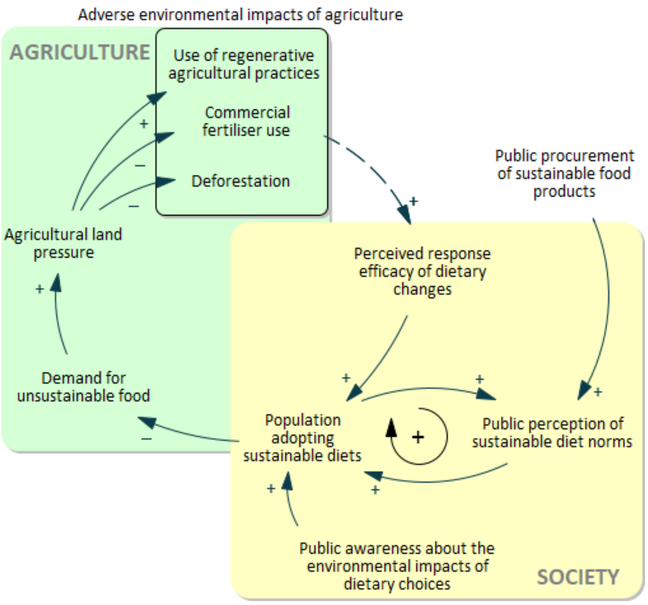

Figure 3. Interaction examples between society and the agriculture sector.

more people adopting the norm, as illustrated by the positive feedback loop in Fig. 3. Since increased availability of plant-based meals at cafés was shown to affect the sales of them strongly (Garnett et al., 2019), public procurement of sustainable food is considered a strategic intervention to accelerate the adoption of new norms (IGS, 2023), and food labelling and certification in alternative food networks (Lenton et al., 2022) is key for facilitating market penetration of alternative proteins. Therefore, such triggers in society and policy can have cascading impacts on intensified and accelerated transformation of food and land use systems.

2.3 Cascading effects in sociopolitical systems

Political systems are often considered the context of positive tipping dynamics in the existing literature as highlighted by Eder and Stadelmann-Steffen (2023), even though they can themselves also change and tip in a positive direction for decarbonization and sustainability. Here, we consider the policies and political system not as a static context but as part of dynamic co-evolutionary tipping mechanisms. For instance, the interaction between society and policy can be key to tipping global carbon emissions by creating cascading effects through individual action, social conformity, public discourse, climate policy, and technological learning. For example, simulation results suggest that individual action is ineffectual unless the social credibility of costly behavioural change is high (Moore et al., 2022). Similarly, based on a literature review of tipping and transition studies, Mey and Lilliestam (2020) identify the key variables that help in monitoring tipping dynamics in the interaction of society and politics. Those are social acceptance of climate science, public support for and trust in government, civil engagement, participation in public consultations, and number of NGOs focusing on climate and environmental problems and share of citizens active in these organizations. Below we discuss additional variables and mechanisms of society's influence on policy and politics as summarized in Fig. 1.

Society affects policy and pushes for stronger climate policies in multiple ways. First, adoption of niche technologies signals readiness for, and higher social acceptability of, wider policy change. Early cost reductions reinforce the policy ambition towards stimulating such technologies further, and coalitions of early adopters influence politics toward a more aggressive policy response (Schmidt and Sewerin, 2017). Societal readiness affects pro-environmental policies, especially on a local scale, as exemplified by different car-sharing policies of local authorities in the Netherlands (Meelen et al., 2019), different solar photovoltaic policies of German states (Dewald and Truffer, 2012), and the positive tipping dynamics observed in the UK's offshore wind production and EV sales due to policies following increasing public concern and attention (Geels and Ayoub, 2023). Second, social movements affect policy, either in legislation or in agenda setting. Civic action preceding and during the annual climate change conferences, that is the Conference of the Parties (COP) (Carattini and Löschel, 2021), and resistance to local fossil fuel projects have been able to cancel or suspend the projects (Piggot, 2018; Temper et al., 2020) or created non-fossil-fuel energy policies (Hielscher et al., 2022). In a third and fundamental way, society influences policy through the election of politicians and policymakers. In Europe and the US, for instance, public risk perception has resulted in green voting after extreme climate events (Hazlett and Mildenberger, 2020; Hoffmann et al., 2022), even though income and political identity play a strong mediating role. Therefore, society provides the political legitimacy and democratic mandate that policymakers need to support radical policy change (Willis, 2020; Smith, 2023).

Another sociopolitical phenomenon that can trigger a tipping cascade is the spike in climate litigation cases worldwide. Climate litigation describes administrative, judicial and other investigatory cases that raise issues of law related to climate change, and it reflects underlying sociocultural changes. Since 2015, climate litigation cases have more than doubled worldwide, surpassing 2000 in May 2022 (25 % of all filed between 2020 and 2022) (Setzer and Higham, 2022). They reflect climate action from diverse citizens (e.g. children in Germany or the Netherlands, grandmothers in Switzerland, a Peruvian Farmer against a German energy company) in various jurisdictions – against governments, banks, and large corporations in emission-intensive sectors – to advance climate action or to challenge which climate policies are implemented and how they are enforced.

Policies have a direct and significant impact on society by creating an enabling environment for the adoption of low-carbon technologies and behaviours through financial support, infrastructure design, regulations, standards, and bans. For instance, subsidization of low-carbon energy (Otto et al., 2020) or transport modes and tax benefits of electric vehicles (Sharpe and Lenton, 2021) are government-led positive tipping interventions that can accelerate the adoption of these technologies and create cascading effects on energy and transport systems. Moreover, policies have a secondary impact on society by signalling what is socially approved or disapproved and setting social norms (Hoff and Walsh, 2019), according to a mechanism called the "expressive function of law" (McAdams, 2015; Sunstein, 1996). Several studies confirm the expressive function of law in other contexts, such as compulsory voting in Switzerland (Funk, 2007), legalizing same-sex marriage in the US (Tankard and Paluck, 2017), and social-distancing policies during COVID lockdowns in the UK (Galbiati et al., 2021).

The tipping of sociopolitical systems can also be triggered by public discourses that have cascading effects on public opinion, political priorities, policy-making, legitimacy, credibility, social norms, values, and mobilization (Bradford, 2016). For instance, the Nobel Peace Prize awarded to the IPCC and Al Gore in 2007 marked a tipping point in climate change discourse (Walsh, 2007), contributing to increased global awareness, strengthened political commitment, enhanced credibility for the IPCC, and catalysed climate activism and influencing future global agreements and sub-national actions (Schiermeier and Tollefson, 2007). Similarly, the Earthrise image taken by the Apollo 8 mission crew in 1968 (Poole, 2008) served as a tipping point contributing to a shift in public opinion and environmental awareness (Schroeder, 2009). This and similar images produce what is known as the "overview effect" (Yaden et al., 2016), evoking a sense of awe and interconnectedness with Earth's systems and inspiring international cooperation in addressing environmental challenges (Logan et al., 2020). The photograph influenced the development of environmental policies and regulations, such as the creation of the Environmental Protection Agency (EPA) in the United States (Collins et al., 2013). Reframing international climate policy from burden sharing to win–win (Jaeger et al., 2012) is considered a key factor leading to Paris Agreement's acceptance, and such transformative win–win narratives in economic, cultural, and financial contexts can also accelerate climate action (Hinkel et al., 2020).

Policies can also create tipping cascades by affecting society through the political–economic system. The societal paradigm shift towards a global neoliberal capitalist economic system in the late 1970s is an intriguing example of a whole society cascade of change. The crisis of Keynesianism in the late 1970s, the collapse of the Bretton Woods system, the oil price shocks, and trade union disputes caused a shift in public opinion and provided the political opportunity for neoliberalism, which used state power to expand the role of markets, competition, and individual responsibility in society. Prior to its ascendency, the neoliberal project had spent 50 years developing a coherent philosophy, a compelling narrative, a detailed policy portfolio, and a network of political support ready for favourable conditions to emerge (Davies and Gane, 2021; Newell, 2019; Brown, 2015; Mirowski and Plehwe, 2015; Burgin, 2012). The historical lessons to be learned in relation to society-wide tipping cascades include the importance of having a portfolio of policies and an effective advocacy coalition ready for a window of political opportunity.

Besides the broader economic system they create, the economic influence of policies on society can lead to positive or negative cascades in more specific ways. For instance, as the economy moves away from fossil fuels, the economic output and thus resulting government revenues from carbon-intensive industries are likely to shrink (Agarwal et al., 2021), which is also the case for those from the industries to be impacted adversely by climate change, such as tourism and agriculture (Bachner and Bednar-Friedl, 2019). Moreover, some countries are heavily reliant on fossil fuel taxes for generating government revenues. For example, a climate policy package focused on long-term decarbonization across the economy in India is estimated to reduce government fuel tax revenues by nearly 70 billion USD (2018) by 2050 (Swamy et al., 2022). On the other hand, mechanisms like mitigation taxes may create new government revenue streams. For instance, a carbon price of USD 50 t^{-1} of CO_2 in 2030 is estimated to lead to a rise in government revenue amounting to approximately 1 % of GDP for several G20 nations and significantly higher increases in some countries (IMF/OECD, 2021). The net impact on government revenues from such varied streams is dependent on innovative policy design for revenue recycling and reuse and can have cascading societal implications on education, infrastructure, and healthcare expenditure, which are the means to tip society through awareness and an enabling environment.

3 Harnessing the power of cascades

Supporting positive cascades is a challenging task, in particular when considering the complex interaction with negative (undesirable) cascades in the human–Earth system, which can disrupt positive cascades. In this section, we briefly discuss how this complexity can be tackled in research and governance so that the potential of tipping cascades can be realized. Below, we focus on (i) how multiple agents and actors can be engaged in the governance of positive tipping cascades to ensure a just transition and (ii) what science can do to support such governance of cascades.

3.1 Governance of positive tipping cascades

Intervention design for positive tipping should balance reinforcing and dampening feedback mechanisms in order to ensure that the abovementioned positive feedback mechanisms will be activated in a desired direction. Therefore, governance of tipping cascades faces tremendous uncertainties about natural and social impacts and responses (Franzke et al., 2022). At heart the governance challenge is to set in motion these feedback dynamics which are, by definition, hard to control. Responding to what unfolds will surely need adaptive governance to avoid negative outcomes, especially for the most vulnerable and impacted groups. Before seeking to trigger tipping, care is needed to consider who can lose from it, involve all stakeholders, and put social safety nets in place. Therefore, diverse sources of knowledge can help to contain this uncertainty and design (more) just transitions in terms of overall human wellbeing, including scientific data and modelling and local and indigenous knowledge based on experience, mobilized through participatory approaches and collective learning.

Polycentric governance was considered a key principle to trigger and guide positive tipping dynamics (Pereira et al., 2023), which can also be applied to the governance of cascades. Not only public authorities and governments but also many different agents can play a role in triggering the cascades because constructive and mutually adaptive behaviour of agents can induce positive tipping cascades across the sociotechnical, socioecological, socioeconomic, and sociopolitical system interactions. For instance, thought leaders and media can be pivotal in enhancing the visibility of a population already engaged in climate action or creating a new public discourse. This determines not only the demand for low-carbon goods and services but also increases the momentum of climate policies and the perceived risk of fossil fuel assets. When such policies and financial developments reduce the fossil fuel supply, the resulting lower costs of low-carbon technologies lead to more people taking climate action by choosing low-carbon options and creating a reinforcing feedback loop of cross-system cascades (Eker and Wilson, 2022). Therefore, governance of tipping cascades can benefit from acknowledging the role of various actors and creating an enabling environment for all of them to function.

To understand how to get to the tipping point and to design and operationalize positive tipping across sociopolitical sectors, scales, and institutions, we can start with understanding the ecologies and dynamics of the key actors and coalitions – including those who oppose or seek to delay climate action, as well as those who support it. We can then use systems thinking across all sectors, scales, and research domains to create a shared understanding of how a wide coalition – including local authorities, political parties, artists, NGOs, businesses, financial investors, trade unions, farmers, faith groups, academics, journalists, lawyers, and social movement organizers – can contribute to a coordinated programme for accelerating climate action within their spheres of interest and influence. In addition to mobilizing active supporters, this programme would also need to include strategies for attracting new recruits and for moderating opposing discourses to ensure a just transition.

3.2 Future research to support the governance of positive tipping cascades

This paper presents examples of potential positive tipping cascades, which are distilled from the emerging literature on positive tipping dynamics. Future research can identify a more complete range of positive tipping cascades more systematically. Expert elicitation, systems mapping, and systematic literature reviews can facilitate delineation of cross-system interactions that can possibly enable and impede positive tipping cascades, as exemplified in Eker and Wilson (2022). Case studies of historical tipping dynamics (Stadelmann-Steffen et al., 2021), local decarbonization (Tàbara et al., 2022), or statistical analyses on time series data cross-system connections, such as finance and economic development (Chakraborty and Mandel, 2022), can support the identification and understanding of these connections, whereas future-oriented modelling studies help analyse their potential to trigger positive tipping cascades. Furthermore, a typology of cross-system interactions underlying positive tipping cascades would enhance the communication and prioritization of research efforts. Such a typology can categorize the identified interactions in terms of their scale (local, national, global), their speed of change (days, years, decades), and the agents who can manage or participate in directing those interacting systems towards the tipping point.

Scientific efforts can focus on integrated human–Earth system models capturing the feedback mechanisms that are identified as potential drivers of tipping dynamics and support intervention design for tipping cascades. Scientific literature contains several examples of modelling studies that explore positive tipping dynamics and interventions in specific contexts (Niamir et al., 2020; Eker et al., 2019; Moore et al., 2022; Juhola et al., 2022), using various methodologies such as system dynamics (top-down feedback perspective), agent-based modelling (behavioural rules), and social network analysis (spread of cascading events). An integrated modelling framework that captures the cascades across sociotechnical, socioecological, and sociopolitical systems discussed above is, however, still missing, which would be useful in quantitatively assessing the intensity and impact of cascades on positive tipping dynamics. Moreover, the complexity of integrated systems modelling might come at a cost of their interpretability and practical usefulness. To accommodate this potential drawback, a strong stakeholder engagement might be needed when designing modelling interfaces and scenarios as outlined by McGookin et al. (2024), including dimensions of political economy, power, distribution, and justice. Such an integrated systems modelling approach, as elaborated in Eker et al. (2024), can especially include not only the positive feedback loops that underlie positive tipping dynamics but also their coupling with counteracting negative and positive feedback mechanisms. In that way, the plausible potential of tipping dynamics emerging from interconnections not only within specific systems but also across them can be evaluated, and the effectiveness of interventions to trigger positive tipping can be tested.

Participatory approaches are valuable not only in utilizing models in decision support but also in harnessing the power of cascades by establishing a shared understanding and systems thinking among multiple actors and supporting cooperative governance. Cooperative governance coordinates, regulates, manages, and controls interdependent social and political relations among multiple actors, including coalitions and organizations of governmental, intergovernmental, and nongovernmental organizations, all pursuing their own goals and interests. Participatory knowledge co-production is demonstrated to aid in the exploration of solutions, empowering underrepresented voices, mediating power dynamics, reevaluating power structures, handling diversity, and redefining agency (Chambers et al., 2021). Therefore, it can be a useful means to support research and cooperative governance of positive tipping cascades, especially to ensure a just transition.

To overcome the collective action problem and ensure a cooperative, polycentric governance that will support positive tipping cascades, various mechanisms offer promising signs: implementing co-benefits and co-evolution; neighbourhood collaboration; transnational initiatives like city networks; coordination of goals, efforts, and actions for mitigation and adaptation; bottom-up participation complementary to top-down global negotiations; and regulations and norms. Identifying conflict potentials is important to prevent escalation towards a cycle of conflict and instead induce cycles of cooperation between stakeholders. This depends on the societal responses, involving adaptive agents following their motivations, capabilities, and behavioural rules.

4 Conclusions

Cascading effects through interactions across society, policy, and sociotechnical systems such as energy, transport, and agriculture is one of the biggest promises of positive tipping points to create rapid climate and sustainability action. In this paper, we reviewed some of the examples of positive tipping cascades and delineated the feedback mechanisms that can amplify positive tipping dynamics. For instance, the learning effect triggered by wider deployment of electric vehicles lowers the energy storage costs, hence the renewable electricity production costs through better ability to deal with their intermittency and leads to wider deployment of both renewable energy and electric vehicles. Similarly, climate and sustainability policies influence the social norms by implying what is approved in the society, in addition to creating an enabling environment for the adoption of low-carbon technologies, products, and services. Such social change signals readiness for more stringent climate policies in return or puts pressure on policymakers through various channels such as social movements, litigation, and green voting.

Various agents, either public authorities or nongovernmental agents, can trigger positive tipping cascades. For instance, public procurement of sustainable food is considered key leverage to accelerate the adoption of new dietary norms. Food labelling by manufacturers and certification in alternative food networks is key for facilitating market penetration of alternative proteins. Civil society is another agent that can trigger the super-leverage points for climate and sustainability action, for instance by spreading new norms and by influencing the policy. Similarly, thought leaders and communicators have the agency to create new public discourses that can tip the sociopolitical systems. Therefore, implementing interventions to trigger positive tipping cascades and managing their dynamic process requires adopting a polycentric governance principle, which can be supported by participatory research approaches to build a shared understanding and consensus between stakeholders.

Future research can identify a more extensive and relevant list of cross-system interactions, for instance with expert elicitations and systematic reviews. The potential of these interactions to create positive tipping cascades can be evaluated by integrated modelling studies, which provide a better understanding of the interacting feedback mechanisms and the future dynamic developments they create. Observational data and model-based simulations can demonstrate empirical evidence for interventions that can trigger cascades. Early warning systems that harmonize the high-frequency data and monitor the key cross-system indicators can also support the management of cascades.

Data availability. No data sets were used in this article.

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