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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, -ecological, -economic and -political 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). Positive tipping points describe how social, political, economic, or technological systems can rapidly move to a new system state (Tàbara et al., 2018). In addition to alternative stable states, nonlinearity, positive feedback loops, and limited reversibility as the four fundamental characteristics of tipping points, positive tipping points are marked by desirability and intentionality in advancing decarbonization and sustainability (Milkoreit, 2022). They have gained wide attention as high-leverage opportunities to use limited policy resources most efficiently for rapid decarbonization (Otto et al., 2020) and to counteract the risk of nonlinear climate change due to climate tipping points (Armstrong McKay et al., 2022).

Positive tipping dynamics have been, or can potentially be, observed in various sociotechnical and environmental systems. For instance, subsidy programs and decentralized production can trigger rapid decarbonization in energy production and storage,

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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, policy etc., and across different scales such as individual, national, international etc. These secondary impacts, called cascades, result in a much larger eventual impact. 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 decarbonisation.

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., 2023).

Here, we describe key examples of cascading effects and feedback loops across various sociotechnical (e.g. energy, transport), social-ecological (e.g. agriculture) and socio-political 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 can be managed by limiting negative cascades and inducing positive ones. In the remainder of this paper, we provide an overview of the positive tipping cascades and review the key examples in Section 2. In Section 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 Section 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

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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 phase-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 decarbonisation 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.

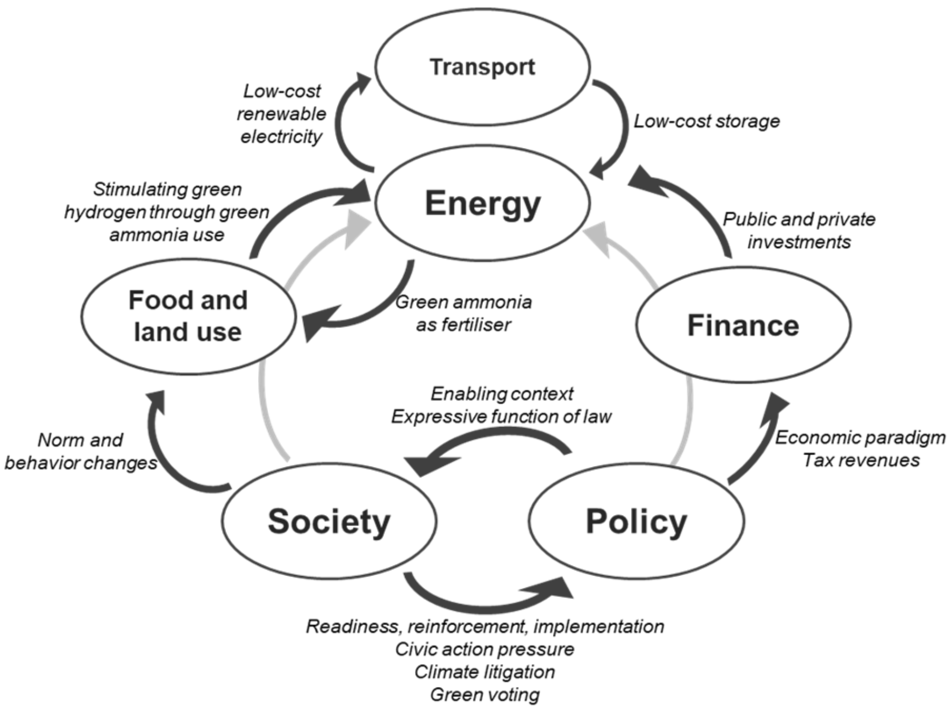

Figure 1: Overview of the cross-system interactions that can create positive tipping cascades. Arrows refer to the cross-system interactions, and the main mechanisms of these interactions are annotated near the arrows.

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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, 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.

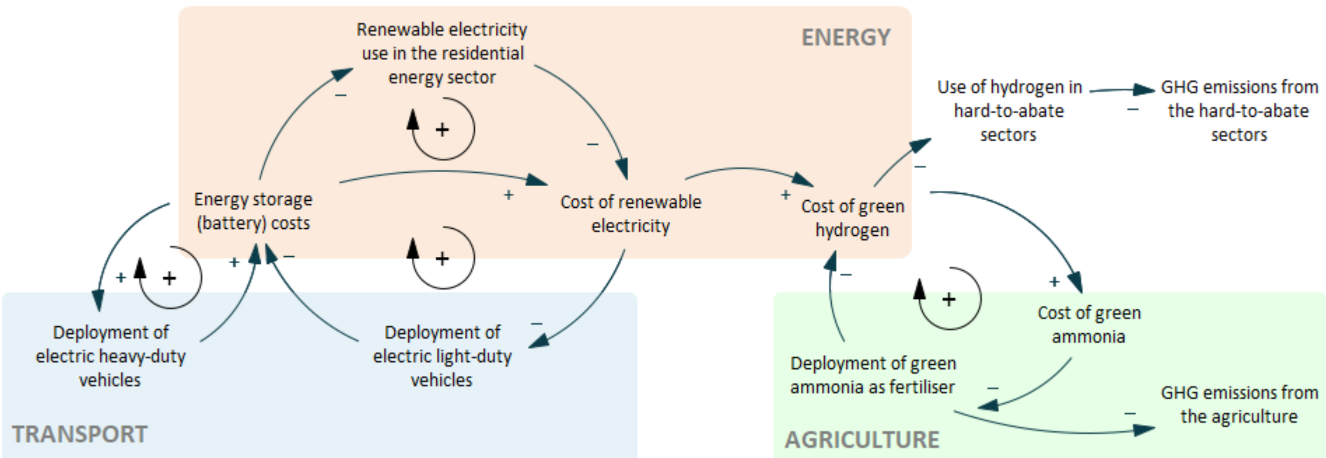

Figure 2: Interaction examples between the energy, transport, and agricultural systems. Using the notation of causal loop diagramming, a positive link from variable A to B means that a change in A leads to a change B in the same direction, whereas a negative link implies a change in the opposite direction.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

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

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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 digitalisation, this spurs decentralisation 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 decarbonise using green hydrogen and its derivatives. For instance, green ammonia (produced from hydrogen with renewable energy) can be used for agricultural fertilisers, 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; Bouaboula et al., 2023). Green ammonia is already cost competitive in fertiliser 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 fertilisers could bring down the cost of green hydrogen for use in several other sectors. For example, implementing a 25% green ammonia blending mandate in fertiliser 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 $1.5/kg 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.

2.2 Cascading effects in socio-ecological systems

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

The role of society is considered a key driver of transformation in the food system, as 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 and averting biodiversity loss, and reducing the intensity of trade-offs between them (van Vuuren et al., 2018; Leclère et al., 2020; Obersteiner et al., 2016).

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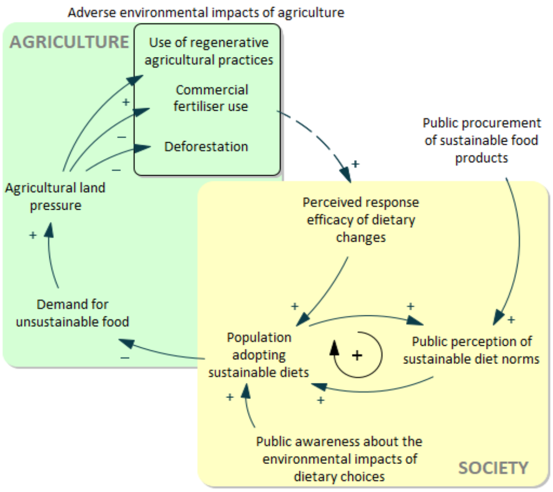

Figure 3: Interaction examples between the society and agriculture sector

As illustrated in Figure 3, dietary behaviour changes towards sustainable food consumption reduce land pressure. As the land pressure declines, fertiliser consumption is expected to decline, and adoption of diversified and regenerative farming practices are expected to increase (Gosnell and Gill and Voyer, 2019), as well as ecological restoration and associated carbon sequestration, leading to more rapid decarbonisation 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 studies (Elliot, 2022; Eker and Reese and Obersteiner, 2019). As more people adopt sustainable diets, the visibility of it will lead to a stronger perception of the sustainability norms, leading to more people adopting the norm, as illustrated by the positive feedback loop in Figure 3. 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

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).

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 reinforces the policy ambition towards stimulating such technologies further; and coalitions of early adopters influence politics for more aggressive policy

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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 and Frenken and Hobrink, 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 an 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 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 create non-fossil fuel energy policies (Hielscher and Wittmayer and Dańkowska, 2022). In a third and fundamental way, society influences policy through the election of politicians and policymakers. In Europe and 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 socio-political 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 2,000 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 how and which climate policies are implemented.

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, subsidisation 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 socio-political 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 mobilisation (Dryzek, 1998; 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

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for the IPCC, catalysed climate activism, and influenced 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 and Genet and Christian, 2013). Reframing international climate policy from burden sharing to win-win (Jaeger et al., 2013) is considered a key factor leading to Paris Agreement's acceptance, and such transformative win-win narratives in the 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 fifty 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 of, hence the government revenues from carbon-intensive industries are likely to shrink (Agarwal et al., 2021), as well as 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 decarbonisation 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.as For instance, a carbon price of $50 per tonne 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

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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 just(er) transitions in terms of overall human wellbeing, including scientific data and modelling as well as local and indigenous knowledge based on experience, mobilized in participatory approaches and collective learning.

Not only public authorities and governments, but 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 socio-technical, -ecological, economic, and -political 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 operationalise positive tipping across socio-political 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

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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 organisers –can contribute to a coordinated program for accelerating climate action within their spheres of interest and influence. In addition to mobilising active supporters, this program 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

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 and Ivanova and Filatova, 2020; Eker and Reese and Obersteiner, 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. Moreover, the complexity of integrated systems modelling might come at a cost of their interpretability and practical usefulness. A strong stakeholder engagement might be needed when designing modelling interfaces and scenarios, including dimensions of political economy, power, distribution and justice.

Participatory approaches are valuable not only in utilising models in decision support, but also in harnessing the power of cascades by establishing a shared understanding and systems thinking among multiple actors as well as supporting cooperative governance. Cooperative governance coordinates, regulates, manages and controls interdependent social and political relations among multiple actors, including coalitions and organisations of governmental, intergovernmental and non-governmental 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 collective action problem and the tragedy of the commons, various mechanisms offer promising signs of supporting positive tipping cascades: 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.

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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 them. 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 non-governmental agents, can trigger positive tipping cascades. For instance, public procurement of sustainable food is considered a 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.

Future research can support the management of positive tipping cascades by providing a better understanding of the interacting feedback mechanisms and the future dynamic developments they create, as well as by creating empirical evidence on interventions that can trigger cascades, either based on observational data or model-based simulations. Early warning systems that harmonize the high-frequency data and monitor the key cross-system indicators can also support the management of cascades.

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Competing interests. The authors declare no completing interests.

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