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Harnessing social tipping dynamics: A systems approach for accelerating decarbonization

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SUMMARY

Social tipping points are promising levers for accelerating decarbonization progress. They describe how social, political, economic, or technological systems can move rapidly into a new state if positive feedback mechanisms are triggered. Analyzing the potential for social tipping requires the inherent complexity of social systems to be considered. Yet the growing social tipping literature is missing a practical framework that embeds conceptual and empirical aspects of complex feedback processes. In this perspective, we propose a dynamic systems approach that can contextualize conceptual social tipping mechanisms into practical interventions, and map the key feedback mechanisms underlying tipping dynamics across systems and scales. Our approach has three main components: a systems outlook involving interconnected feedback mechanisms; directed data collection for empirical evidence and monitoring tipping dynamics ; and global, integrated, descriptive modeling to project future dynamics and provide *ex ante* evidence for tipping interventions. We demonstrate how and why this approach should shape a broad agenda to strengthen the viability and effectiveness of social tipping research.

INTRODUCTION

The urgency for rapid and sustained reductions in greenhouse gas (GHG) emissions has drawn the attention of scientific and policy debates to social tipping (ST) points[1,2] that can trigger accelerated climate action through cascading effects in societies, institutions, and economic systems once a critical threshold is crossed. As a result, ST points have gained wide attention as a high-leverage opportunity to counteract high-risk climate tipping points[3] and to use limited policy resources most efficiently.[4]

ST points describe how social, political, economic, or technological systems can move rapidly into a new system state or functioning.[2] The term often refers to nonlinear state change, without a clear distinction from similar phenomena such as regime shift and critical transition.[5] A growing scientific literature is developing a definition and theory of ST mechanisms, either through analogy with climate tipping mechanisms[1,6] or by using a sociotechnical transitions perspective.[2] For instance, Milkoreit et al.[7] seek a common definition by comprehensively surveying literature trends with various keywords related to ST. They find a rising publication count from the mid-2000s, dominated by disciplines of socioecological systems, climate change, and economics. Their content analysis of tipping point definitions emphasizes positive feedback structures as the core driver of nonlinear transitions between multiple stable states with limited reversibility, as well as multi-scale processes and cascading effects between systems.

In addition to these four key attributes of tipping points—alternative stable states, nonlinearity, positive feedbacks, and limited reversibility—ST points are characterized in the literature by desirability and intentionality in support of decarbonization and sustainability.[5] For these normative reasons, there is also an emerging trend to use the term "positive tipping" instead of ST,[8] even though there is inherent subjectivity in what is desirable and positive. For instance, what is considered positive for some groups or subpopulations may be considered undesirable for others. The term "social tipping" helps avoid the subjectivity of positive tipping, and it can also involve adverse ST if the positive feedback mechanisms that underly tipping dynamics function in an adverse direction. Furthermore, social systems involve complex sets of interacting drivers and mechanisms and do not

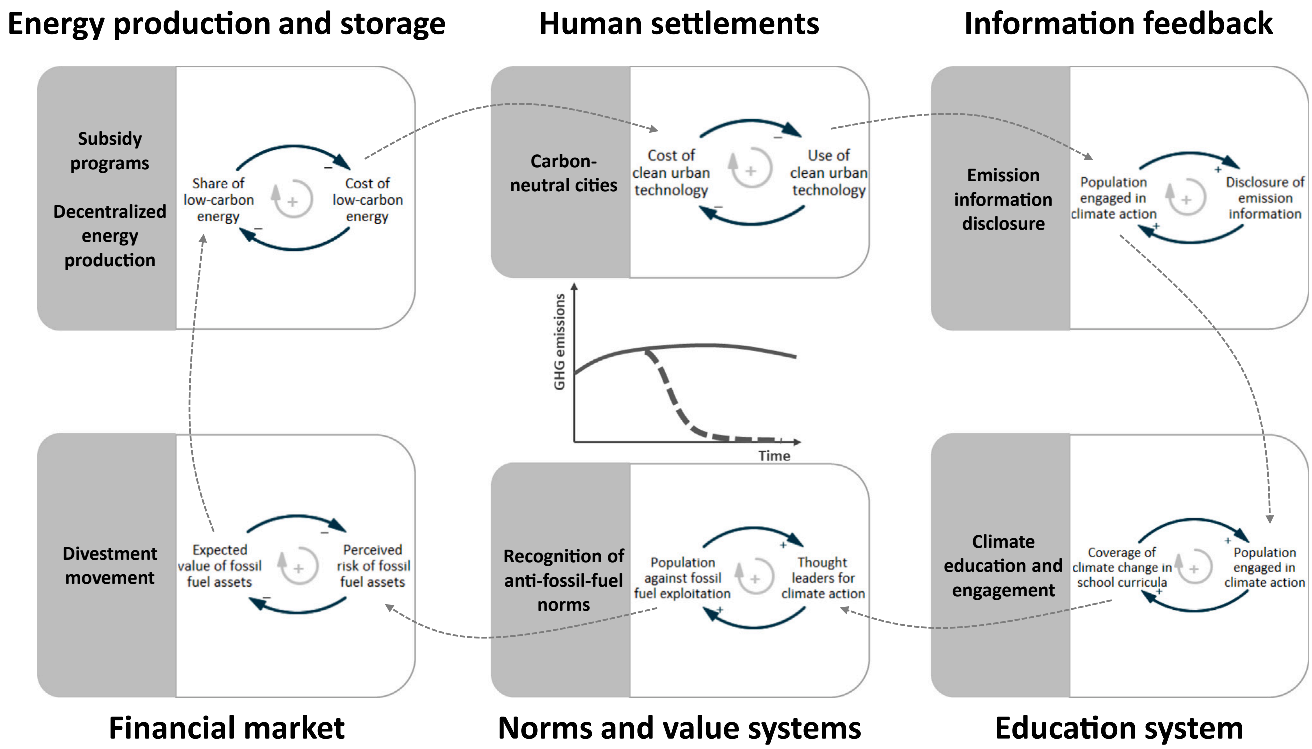

Figure 1. Stylized depiction of six social tipping elements for rapid decarbonization
Social tipping elements (STEs) identified by Otto et al.[1] refer to social systems in which tipping dynamics toward rapid decarbonization can be observed due to positive feedback loops (depicted for simplicity without the delays they involve). The interventions that can trigger tipping dynamics in each element are noted in gray. Besides the feedbacks within them, STEs have interconnections that can create cascading effects.

have a single control variable,[6] which make single points or critical thresholds difficult to isolate.[9] Therefore, ST "processes" or "dynamics" can be a more suitable term instead of ST "points."

The existing literature on ST dynamics is currently missing a practical framework that embeds conceptual and empirical aspects of ST processes in order to inform decision-making. It also tends to overuse and misuse the term "tipping point."[5] As a result, the large potential beneficial impact of ST is undermined by weak analytical understanding due to limited and biased methods.

Here, we unpack the challenges that impede a strong analytical understanding of ST and then propose a dynamic systems approach to tackle them. This dynamic systems approach addresses both the scientific purpose of a foundational understanding of the system dynamics (SD) of ST and the instrumental purpose of identifying effective tipping interventions. It integrates three main components: first, a systemic outlook on ST mechanisms that takes into account not only reinforcing but also impeding feedback mechanisms, as well as cascading effects across different subsystems. Second, data gathering and harmonization provides empirical evidence and helps monitor the effectiveness of interventions. Third, dynamic simulation modeling assists with exploring the collective and cascading behavior of feedback mechanisms and creates *ex ante* evidence for effective ST interventions. We demonstrate examples of how such a dynamic systems approach can be put into practice by mapping the key feedback mechanisms underlying tipping dynamics across systems and scales. We conclude that such a systems approach can strengthen the understanding of ST dynamics and their relevance for various agents and decision-makers.

WHAT WE KNOW SO FAR ABOUT ST

Social systems in which tipping can occur

Several social systems can exhibit tipping dynamics. For instance, based on expert elicitation and literature review, Otto et al.[1] have identified six "social tipping elements," that is, social, political, economic, or technological systems in which tipping processes toward rapid decarbonization can occur. Shown in Figure 1, these are: (1) energy production and storage, where subsidy programs and decentralized production can trigger rapid decarbonization through their cascading impacts not only on costs but also on consumer preferences and norms; (2) financial markets, where divestment from fossil fuels can rapidly reinforce investors' belief in the risks of carbon-intensive assets; (3) education, where climate change coverage in school curricula can trigger sustained widespread engagement in climate action; (4) norms and values, where advocacy by a few thought leaders can lead to a large population recognizing anti-fossil-fuel values; (5) urban infrastructure, where choosing clean technologies can trigger both cost reductions and consumer interest in pro-environmental choices; and (6) information feedbacks, where disclosure of emission information on consumer products can trigger rapid behavioral change. Sharpe and Lenton[10] discuss the adoption of new technologies such as electric vehicles (EVs) and solar photovoltaics as specific examples related to energy and urban infrastructure. Farmer et al.[11] add institutional structures such as the UK Climate Change Act since they can shape long-term and consistent climate policies. Taylor and Rising[12] focus on agriculture and demonstrate the presence of an economic positive tipping point beyond which agricultural land-use intensity starts declining.

One of the biggest promises of ST dynamics is the cascading effects through interactions between the systems. For instance, Otto et al.[1] argue that more emphasis on climate change in the education system can lead to wider advocacy activities that trigger norm and value shifts while creating a higher sensitivity to carbon-emission disclosures on consumer products. Stadelmann-Steffen et al.[13] exemplify cross-system interactions with the historical phaseout of ozone-depleting chemicals (CFCs, chlorofluorocarbons). They consider the Montreal Protocol, non-CFC substitutes, and public concerns over ultraviolet radiation and skin cancer as interacting political, technological, and behavioral tipping elements, respectively. Another example is provided by Pascual et al.[14] who identify the opportunities for positive tipping from the interactions between biodiversity, climate, and society. Simulation results of Moore et al.[15] show a tipping behavior in projected global carbon emissions resulting from cascading positive feedbacks through individual action, social conformity, climate policy, and technological learning. Therefore, accounting for cross-system interactions is crucial for estimating the potential of ST and identifying key interventions, since a single system focus overlooks cascading opportunities.

Besides cross-system interactions, cross-scale interactions can also trigger tipping dynamics, as they result in contagion from individuals or organizations at the micro level to meso-level communities and macro-level countries and the world. For instance, renewable power and EV policies in a handful of frontrunner countries have been shown to accelerate the transition on a global scale across countries and sectors.[10,16,17] Similarly, a single schoolchild's protest has led to the global Fridays for Future movement, and through interconnections with other systems such as policy, is implicated in ST dynamics.[13] Interventions at the meso level of communities (10,000–100,000 people) have been identified as having a maximum leveraging effect for rapid decarbonization,[18] due to cross-scale interactions and pedagogy for agency.[19]

ST interventions

ST interventions are active changes made to social systems in order to trigger or activate tipping processes, including those through cascading effects.[1] Such interventions can be "kicks" that push the system onto a new trajectory without changing the underlying structure (e.g., financial disclosures that trigger the loop between climate risk perception and the value of fossil fuel assets) or "shifts" that change the system rules (e.g., institutional structures such as the UK Climate Change Act that created new institutional bodies and set the conditions under which future governments decide on climate policy).[11] Not every climate change mitigation strategy, measure, action, or policy can be considered a tipping intervention, unless they trigger or create relevant feedback loops underlying tipping dynamics.

National policies such as targeted investments, pricing policies, incentives, and regulations are considered ST interventions focused on feedbacks in specific systems.[10,20] Such interventions can also be triggered by civil society and create the constituency for government-led interventions[6,21] through cross-system interactions. For instance, behavioral interventions like communicating changes in social norms can accelerate demand-side mitigation, and positive spillovers can lead to tipping dynamics within or across consumption domains.[22] Therefore, ST interventions should be distinguished as those that can activate positive feedback mechanisms to trigger cascading dynamics across scales and systems. Subsequently, assessing the effectiveness of ST interventions requires taking counteracting mechanisms into account, such as the negative feedback loops or positive feedbacks that operate in an adverse direction.

Data availability and modeling

Current scientific literature shows an inclination toward narrative-based presentation of potential ST dynamics, where empirical evidence is either in a limited context or expert elicited and not observational. For instance, EV adoption is described as an example of cross-scale tipping dynamics in a narrative form,[10] and possible tipping dynamics of coal phaseout in China is described based on an actor-objective-context framework.[23]

Monitoring tipping processes is a data-intensive yet crucial activity to track if a tipping threshold is approached or exceeded. For instance, the transformation seismograph of the New Climate Institute tracks indicators of tipping processes in power and transport systems.[24] Climate Action Tracker[20] monitors energy system indicators such as cost parity between renewable electricity generation and fossil fuel assets. Systems Change Lab's data dashboard adds industry and finance indicators to these monitoring activities.[25] Similarly, Climate Watch monitors the policy system based on the records of countries that enhance their nationally determined contributions (NDCs) to the Paris Climate Agreement or have net-zero pledges in their law, policy documents, or political pledges.[26]

Quantitative simulations compile empirical evidence on individual systemic relationships from selected literature, market data, or surveys. They then project emerging long-term dynamics and demonstrate the conditions under which tipping behavior occurs. However, existing evidence from simulation studies remains limited to specific single systems, such as dietary change,[27,28] global spread of urban innovations,[29] urban cycling,[30] or ground-water management.[31] The stylized global model of Moore et al.[15] notably combines multiple systems, from public opinion to individual technology adoption, climate policy, and endogenous technological change. It shows that individual action triggers a cascade of positive feedback processes through technological learning and social conformity for climate policy support.

CHALLENGES AND KNOWLEDGE GAPS IN ANALYZING ST

To identify how feedbacks, multiple systems, cascading effects, and evidence for ST dynamics are characterized, we scan the recent ST literature and find that (Figure 2; Note S1) half or more of existing articles are conceptualized as follows: first, they mostly include single systems or scales in their scope

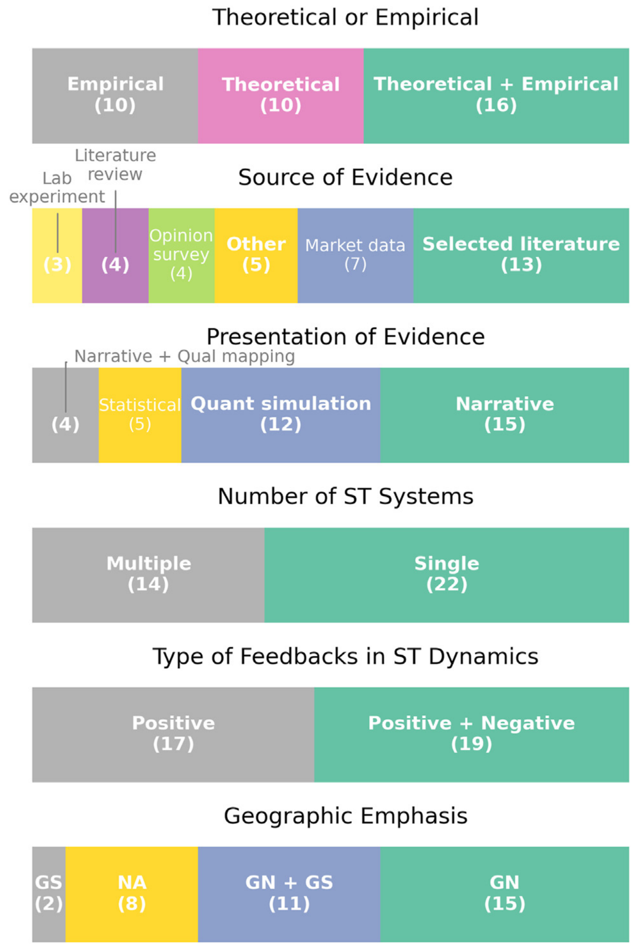

Figure 2. Categorization of the emerging ST literature

The publication data were retrieved from a search on the Scopus database in October 2022 with search terms "social tipping" OR "positive tipping" OR "sensitive intervention points" OR "socio-ecological tipping" OR "socio-economic tipping" in article titles, abstracts, and keywords. This resulted in 59 articles to which we added five more articles identified during an expert elicitation workshop.[9] After screening for relevance, we categorized the remaining 36 articles. The rows of the figure refer to this categorization in terms of whether they provide empirical evidence or remain at a theoretical level, what source of evidence they use for tipping dynamics and how they present this evidence, whether they consider single or multiple ST systems, whether they focus on positive or negative feedbacks, and whether their geographic emphasis is on the Global North (GN) or the Global South (GS) (or "NA" if geographic coverage is not specified). The numbers in parentheses refer to the number of publications in each category. "Other" in the source of evidence row includes parametric evaluations or studies based on expert elicitation and selected literature reviews. The articles and full categorization can be seen in Note S1.

where ST dynamics can occur such as adoption of EV technology in the transport system, instead of multiple or connected systems (e.g., energy, finance, social norms, education) and scales (e.g., community, national, global). Second, they focus only on positive feedback mechanisms that can create the tipping dynamics for rapid decarbonization and sustainability but omit related negative feedback loops or undesired positive feedback loops that create lock-ins in unsustainable technologies and practices. Third, many of these articles present evidence only in narrative or qualitative format for the account of ST dynamics, where the discussion remains mostly theoretical, with empirical evidence obtained from selected literature. Additionally, we observe that many case studies or empirical evidence are from the Global North, overlooking different circumstances of the Global South.

Focusing on single systems

One of the biggest promises of ST dynamics are the cascading effects through interactions between systems, yet these interconnections are not frequently examined, as the dominant single system view in the existing literature shows (Figure 2). This focus on single systems is also observed by Allen and Malekpour[32] in the context of accelerated transformations toward sustainable development goals (SDGs), where much needed multi-system interactions receive only weak attention in the literature. A single system focus without considering cross-system and cross-scale interactions, negative feedbacks, and socioeconomic and geographic differences limits the scope and relevance of intervention assessments. Unlike relatively well-defined climate tipping points, analyzing ST and ST interventions requires an approach that takes into account the inherent complexity of social systems and all the efforts leading up to the targeted tipping point.[33]

Focusing on positive feedback loops

The core driving mechanism of ST dynamics are positive feedback loops; hence, most interventions proposed in the existing studies target those (Figure 2). Intervention outcomes are uncertain due to interactions between reinforcing (positive) and balancing (negative) feedback loops. Systems thinking has established that interconnections between positive and negative feedback loops create complex dynamic behavior beyond the desired one, such as policy resistance, inertia, path dependency, or oscillations.[34,35] An example is that social movement interventions can trigger positive feedback loops of norm and value changes, yet they also lead to value polarization as a countervailing process (see Box 1). For instance, protest movements against both fossil and low-carbon energy projects have stopped, suspended, or slowed new developments but have also led to violence.[36] Polarization also creates a loss of diversity in opinion, ideas, and solutions,[37,38] undermining system resilience and jeopardizing the promise of interacting positive feedbacks for accelerated climate action. Therefore, the formulation of effective interventions can benefit from considering the role of negative impacts to avoid resistance and unintended consequences.

Lack of observational data and model-based studies

The empirical evidence underlying the theoretical, narrative-based discussion on ST often comes from selected, domain-specific literature. A few studies statistically show historical tipping dynamics based on large-scale data, such as the European Social Survey[55] or gridded land use data.[12] A few lab experiments confirm the presence of tipping dynamics created by social conformity,[47,56,57] where adoption of a new norm by 25%–40% of the population (critical mass) triggers further contagion, yet polarization can impede tipping.[47] Even fewer field trials demonstrate the role of critical mass and information feedbacks in a real-life setting.[58] Such contextual and

Box 1. Multiple positive and negative feedback mechanisms governing norm and value changes

Since social and moral norms are key drivers of human behavior,[39] shifting toward anti-fossil-fuel norms is considered a key social tipping process for rapid decarbonization.[1] Advocacy against fossil fuel extraction even by a small group of thought leaders or influencers can stimulate the diffusion of pro-environmental values.[11] The feedback loop norm change against fossil fuels in Figure 3 depicts this reinforcing mechanism of diffusion: thought leaders who advocate for anti-fossil-fuel norm changes can be individuals or organizations within civil society, international organizations, state leaders, and subnational governments.[40] Their advocacy activities are empirically shown to influence public opinion and mobilization against fossil fuel exploitation, as exemplified by the individual influence of Bill McKibben[41] and Greta Thunberg[42] or the student activists mostly influenced by their leaders.[43] As the population against fossil fuel exploitation increases, more thought leaders or norm entrepreneurs emerge from different communities and newly created coalitions,[44] closing the loop of diffusion.

In contrast, the reinforcing loop of norm change for fossil fuels acts as a primary impediment to anti-fossil-fuel norm shifts, since it represents a value polarization cycle commonly observed in climate debate in multiple countries.[45,46] Recent lab experiments also show that identity and polarization are strong impediments to tipping dynamics in a broader context.[47] Pro-fossil-fuel norms develop similarly to the anti-fossil-fuel norms: the population supporting fossil fuel exploitation increases as advocacy about the benefits of fossil fuel exploitation becomes prevalent, as exemplified by the strong relation between public opposition to one of the major US climate policies and views of politicians and certain TV channels.[48] In return, political leaders adopt a polarizing language to appeal to the increasing fraction of population supporting their view,[49] which enhances advocacy activities and makes fossil fuel policies one of the most politically polarized issues, especially in the US.[45] People who are exposed to opposing views stick to their own view more strongly[50]; hence, advocacy activities enhance value polarization and reinforce the norm change feedbacks on both sides. The amplifying effect of partisan identification on climate policy support among both Republicans and Democrats in the US[51] exemplifies the role of such feedbacks.

A balancing feedback mechanism that affects norm shifts is the fossil fuel advocacy loop. As the population against fossil fuel exploitation increases, the resulting social mobilization leads to policies that restrict fossil fuel extraction and use, as observed in many local and national settings so far.[36,52] Regulations restricting fossil fuel use are the main drivers of corporate promotion by the fossil fuel industry,[53] which enhances pro-fossil-fuel advocacy activities[54] and eventually reduces the population against fossil fuel exploitation. This feedback loop potentially dampens the growth of the population against fossil fuels, hence the norm shifts. A similar balancing loop can be formulated due to the media coverage of climate change leading to higher pro-fossil-fuel advertisements,[53] often triggered by advocacy activities of influential thought leaders. The real-world example of fossil fuel resurgence following the war in Ukraine provides an opportunity to examine how these dynamics can play out on the world stage.

methodological limitations of empirical evidence affect the modeling studies that consolidate available data. Modeling studies are based mostly on a Global North perspective (Note S1); hence, they do not constitute strong evidence for whether ST can be observed in the Global South considering the needs of future global consumers and the complexity of local socioeconomic and environmental conditions. Monitoring systems that aggregate national and global data are useful in tracking observed developments, and they can be expanded to social systems to include behavior, norm, and value changes with carefully selected metrics for which data can be collected that indicate tipping dynamics.

The uptake of proposed tipping interventions by policymakers and stakeholders requires clear empirical evidence on their effectiveness. This in turn requires more geographically and contextually comprehensive statistical, experimental, and modeling studies to build the evidence base.

DYNAMIC SYSTEMS APPROACH TO ST

To address the gaps in the conceptualization and assessment of ST points and interventions, we introduce a three-pillared dynamic systems approach with examples developed in an expert elicitation workshop that involved participatory modeling of key ST processes.[9] The three pillars that complement each other are a systems outlook that delineates system structures, data gathering and monitoring tipping dynamics, and dynamic modeling to consolidate available empirical knowledge and evaluate potential interventions.

Systems outlook

Understanding potential tipping dynamics for rapid decarbonization can be enhanced by delineating the underlying system structure based on three principles.

Principle 1: Characterize and map the feedback mechanisms in each ST system by taking potential barriers to positive tipping dynamics into account

ST processes described in many existing studies depict the mental models of experts from physical climate science or social sciences such as transition studies based on sector-specific historical behavior. These mental models often focus on the critical threshold of a tipping process, describe a unidirectional impact from interventions to outcomes, and do not always explicate closed chains of relationships (feedback loops). Delineating the feedback mechanisms, however, can lead to a better understanding of eventual dynamic system behavior.

ST dynamics are expected to occur as a result of positive (reinforcing) feedback mechanisms[59,60] that amplify a change in the same direction through a loop of system elements. Many existing conceptualizations of ST processes emphasize such feedbacks that positively affect decarbonization and overlook the negative ones (Figure 2). Even though tipping dynamics are characterized

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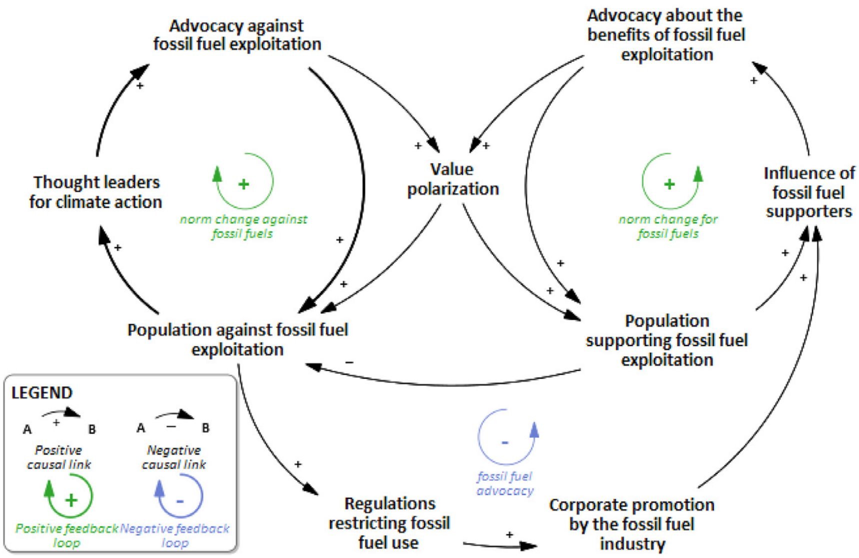

Figure 3. Main feedback loops underlying ST dynamics in the norms and values system, derived from expert elicitation and empirical studies

A positive causal link implies that a change in variable A changes variable B in the same direction, whereas a negative link implies a change in the opposite direction. A positive feedback loop refers to a closed chain of relationships that includes an even number of negative links and where a change in any element, either in the positive or negative direction, is reinforced through the loop. A negative feedback loop refers to a closed chain with an odd number of negative links where a change is balanced through the loop. Positive feedback loops create exponential dynamic behavior, either growth or collapse, and negative feedback loops create balancing dynamic behavior in a system state, either increasing or decreasing. Relevant empirical studies are listed in Note S2.

by reinforcing feedbacks, dynamic systems are characterized by a multiplicity of coupled negative and positive feedbacks.[34] For instance, negative feedbacks and path dependence have been the dominant set of dynamics in energy systems,[61] such as the rebound effects on the demand side or fossil fuel dependence due to capital stock accumulation on the supply side. Another example is the rapid divestment from fossil fuel assets, which is considered a financial tipping intervention,[1] yet it can lead to financial instability and adverse distributional consequences that can undermine system functioning.[9] Diffusion of ethical values against fossil fuel exploitation through social conformity is another key ST process.[1] This reinforcing loop of social conformity is counteracted in reality by the feedback mechanisms of polarization and industry resistance, which might impede the tipping potential of norm changes. Moreover, what may be considered positive tipping in the Global North, e.g., rapid and large-scale decarbonization, may trigger unintended negative consequences in the Global South or marginalized regions, such as the unplanned closing down of wealth-generating markets and export opportunities. Therefore, considering the resistance caused by negative effects and feedbacks provides a more balanced estimate of the tipping potential and helps avoid unintended consequences of interventions.

Multiple methods can be employed in combination to delineate the feedback mechanisms underlying tipping dynamics. For instance, participatory systems mapping methods either based on causal loop diagrams[62] or fuzzy cognitive maps[63] can elicit and align expert views. Qualitative or semi-quantitative models co-developed using these participatory methods can be complemented by literature reviews of available quantitative empirical evidence. Box 1 and Figure 3 exemplify coupled feedback loops delineated in a participatory modeling workshop and supported by empirical studies listed in Note S2.

Principle 2: Identify and map the interactions across multiple systems in the conceptualization of ST processes

The analysis of ST processes tends to be system specific, such as the diffusion of EVs in the transport sector.[10] However, many of these systems are strongly interconnected, as exemplified by the education-society links for shifting to anti-fossil-fuel norms[1] or policy-technology-behavior connections that tipped the phaseout of CFCs.[13] Growing empirical evidence supports the presence of interactions between public opinion, social norms, individual pro-environmental behavior, climate policy, climate impacts (and their effects on opinion), and technological change.[15,64] The dynamic behavior resulting from these cross-system interactions that potentially lead to additional feedback mechanisms might accelerate tipping dynamics and boost the effectiveness of interventions, or vice versa.

The examples of cross-system interactions provided so far are limited in scope, and further interconnections can be identified and analyzed, for instance, between education, finance, and energy systems. Estimating and validating the tipping potential of interventions can benefit from maintaining a feedback perspective in specifying these interconnections, rather than formulating them as linear cascading effects. Empirical support for cross-system interaction is also important.

Participatory approaches with experts and stakeholders from different communities can facilitate the interdisciplinary research needed to identify existing and potential cross-system interactions. While providing quick access to well-informed mental models and available empirical evidence, participatory research can also steer new empirical research for quantifying cross-system interactions. Participatory approaches themselves can also contribute to ST through their impact on social movements.[65] Box 2 and Figure 4 exemplify interactions between energy, finance, urban infrastructure, policy, and society delineated in a participatory modeling workshop and supported by empirical studies listed in Note S2.

Principle 3: Identify and map the interactions across multiple scales in the conceptualization of contagion dynamics that lead to ST

Social contagion among individuals is a strong feedback loop that triggers tipping dynamics.[83] Contagion can also be observed among and across communities, firms, authorities, and nations,[84] resembling fractals that replicate the same structure.[19]

Box 2. Cross-system interactions

Energy, finance, policy, societal, and urban infrastructure systems involve positive feedback mechanisms that can individually lead to social tipping dynamics.[1,9] They also interact with each other through linear cascading effects and wider feedback loops that can amplify or dampen the tipping dynamics. Figure 4 depicts those interactions, which are mapped in an expert elicitation workshop and follow the empirical studies listed in Note S2.

The loop "fossil fuel (FF) financing through market presence" shows a coupling of finance and energy systems: the higher the FF energy supply, the higher the demand, leading to a higher expected value of FF assets,[66] hence more investment and higher FF energy supply[67] (and the reverse applies). This feedback loop is further reinforced by the credibility of emission reduction commitments. If investors trust climate policy announcement and introduction, they will revise their risk assessment for FF firms, leading to a higher cost of capital for FF investments, lowering profitability and thus the FF asset value.[68,69] The credibility of commitments leads also to a lower cost of capital for renewable energy investments, further enabling decarbonization. The credibility of commitments is reduced by a continuing high demand for FFs but enhanced by the strength of the climate policies themselves.[70] These two reinforcing feedback loops on FF financing could create positive tipping if they function in a direction that decreases the FF energy supply, yet they can lead to a strong lock-in in FFs otherwise. The expected value of FF assets is also dependent on perceived climate change impacts,[71] which creates the balancing feedback loop of "FF financing through externalities," as diminishing the FF supply would reduce the climate impacts in the long term. This feedback loop is expected to balance either the increase or decrease of the FF energy supply in the future.

Another major driver of the expected value of FF assets is the momentum of international climate policies. For instance, the Paris Agreement led to a significant reduction in high-carbon stock values and an increase in the cost of borrowing.[72] International climate policies eventually reduce the FF supply through not only their financial impacts but also their direct impact on national regulations restricting FF use.[73] National policies such as carbon tax or emission trading focus on FF consumption, yet those restricting supply have gained momentum.[74] Their impact on global FF supply is yet to be achieved,[75] as the location of such policies and FF extraction match.[76]

The balancing loop "social legitimacy of climate action" depicts the influence of social changes on the FF energy supply through finance and policy: the population engaged in climate action through direct mitigation behaviors such as energy saving or civic action enhances the momentum of international climate policies by putting pressure on negotiations and signaling a readiness for national policies.[77] Worsening climate change impacts increase the engagement in climate action either directly[64,78] or indirectly via thought leaders[79] who communicate climate change causes and solutions. Climate impacts are dependent on FF energy supply, which can be traced back to the momentum of climate policies. It is important to note that there are further feedback mechanisms not visualized in Figure 4, for instance, the negative impact of regulations restricting FF use on the population engaged in climate action through corporate lobbying and value polarization, as discussed previously (Figure 3).

The enabling social pressure loop depicts the connection of urban infrastructure, energy, policy, and finance systems: the provision of low-carbon urban technology can facilitate low-carbon behaviors such as reducing household waste and energy use[80] or cycling,[81] increasing the population engaged in climate action and eventually lowering the FF energy supply. This in return can reduce the cost of low-carbon energy and subsequently the cost of low-carbon urban technologies that rely on low-carbon energy such as transport and heating, resulting in further provision of low-carbon urban technology.[82]

Acknowledgment of different scales of agency and their cross-scale interactions may help to overcome the fractal carbon trap[16] by shifting decision-making agency away from attribution to a single scale, actor, or ideology (such as free-market solutions to social, economic, and environmental problems) and toward diverse, multi-level, catalytic action at different scales.

System conceptualization can explicate the scale of each tipping mechanism, such as individuals, multi-national corporations, or national governments, and identify the bi- or multi-lateral interactions between those scales. Box 1 exemplifies the contagion effects among individuals and how these relate to firm-level actions and national policies. Such an explicit account of different scales of action and their interactions also helps formulate tipping interventions to fulfill the dynamic needs of society and capture opportunities beyond achieving a static goal such as emission reductions.[85]

Data gathering and harmonization

Complementing the system conceptualization described above, dedicated data collection efforts are needed to move beyond specific, single-system data from selected literature, to consolidate empirical evidence for conceptual feedback loops underlying tipping dynamics as exemplified in Boxes 1 and 2, and to monitor the actual or potential effectiveness of interventions. Time-series data on the state of various systems and their interactions help us to understand the rate of change in those systems, which indicates whether a rapid change begins. The observed behavior patterns also help us to understand which feedback loops govern developments, as exemplified by Geels and Ayoub[86] in the case of accelerating offshore wind and EV adoption.

Data collection requires identifying the key indicators that can represent the dynamics created by coupled feedback mechanisms and interventions. For instance, cost parity between low-carbon and fossil fuel energy supply combines the dynamics of technological learning and economies of scale feedbacks both from the low-carbon and fossil fuel energy sector. Box 3 and Figure 5 exemplify two monitoring variables identified in an expert elicitation workshop and their stylized tipping trajectories.

Monitoring ST dynamics requires harmonizing different sources of time-series data over common time frames to enable

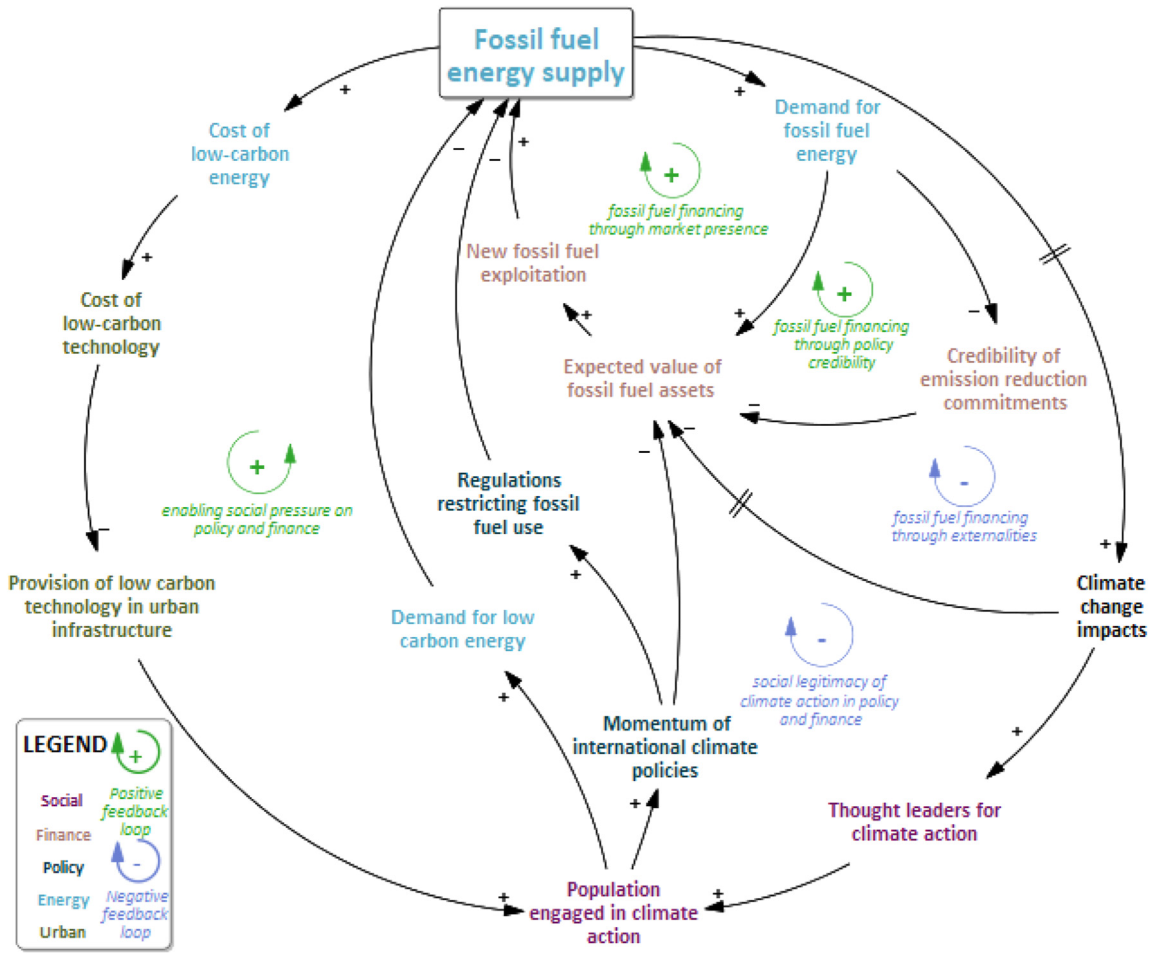

Figure 4. Main feedback loops resulting from the interactions between energy, finance, urban, social, and policy systems, derived from expert elicitation and supported by 27 empirical studies

Double lines on arrows indicate a delay in the relationship depicted by that arrow. See the caption of Figure 3 for an explanation of the notation. Feedback loops are supported by 27 empirical studies listed in Note S2.

the detection of cascading cross-system changes. For instance, social media data can be used as high-frequency, publicly available, and low-cost global sources[87] to monitor the norm and value changes in social systems, in combination with purposeful, lower-frequency data such as the World Values Survey.[88] Harmonizing these data on norm and value changes with records of other systems, such as international and national policy action, energy cost parities, technology adoption levels, and financial flows, can help to quantify the bilateral cross-system relationships and monitor their cascading effects toward tipping. Sharing these harmonized data on online platforms can facilitate further in-depth collaborative research within scientific communities, whereas public display can demonstrate the importance of rapid action. Harmonized time-series data for the indicators of tipping dynamics is also crucial for quantifying simulation models, as discussed in the following section.

Dynamic modeling

Modeling is a key tool in analyzing and navigating dynamic systems, helping to understand how a system works, and bringing rigor to the analysis with an explicit formulation of ideas and assumptions, consolidation of data, and logical tracing of those formulation sequences. Models, either qualitative or quantitative, provide a future outlook by estimating how a variable is likely to evolve, diagnosing what factors have the greatest leverage to change outcomes, and assisting in *ex ante* policy assessments. In the ST context, quantitative modeling is commonly used (Figure 2) to demonstrate the conditions under which tipping occurs, yet in stylized cases and mostly from a single-system perspective.

Dynamic modeling can support the analysis of ST dynamics by embedding four key aspects. First, models should enable a systematic demarcation of interconnected feedback mechanisms within multiple systems and their cross-system and cross-scale interactions from the micro to the meso and macro levels. Second, the models should be grounded in representative data and move toward the quantitative realm for computational analyses of feedback dynamics. Quantifying social systems at a global level is challenging, and aggregation in stylized representations is unavoidable. Still, quantitative methods aligned with

Box 3. Monitoring social tipping dynamics

Monitoring social tipping dynamics requires operationalizing variables that can capture the cascading feedback dynamics in multiple systems. Below are two examples of such variables, with Figure 5 presenting a stylized potential trajectory of each variable.

The number of systemically important companies calculating climate value-at-risk is an indicator of climate risk perception in financial markets, hence the perceived risk of fossil fuel assets. Systemically important companies can be defined as those that have more than $100 billion in assets. We estimate this variable to have grown increasingly in recent years, but the critical threshold is yet to be achieved.

Willingness to pay for climate action can be used to monitor the population engaged in climate action, for which data have already been collected and used in some contextual studies. Willingness to pay is heavily dependent on income level and economic situation; hence, it is expected to fluctuate over time depending on economic cycles. In the middle-income group, willingness to pay is expected to have an increasing future trend, whereas it is estimated to be well below a critical threshold currently in the low-income group.

global data can provide actionable evidence for the long-term effectiveness of interventions, while qualitative and participatory approaches facilitate the conceptualization and dissemination of such quantitative modeling. Third, to tackle the broad scope of multiple social systems and feedbacks, an iterative modeling approach can help, where broad system boundaries are narrowed down through empirical support and computational diagnostic analyses, and further research efforts are dedicated to those feedbacks that are shown to be more important. Fourth, interdisciplinary modeling can ensure policy relevance through either hard or soft coupling between models of tipping dynamics and existing climate policy models.

A modeling discipline that has widely and influentially guided climate policy assessments is integrated assessment modeling (IAM),[89] yet it is limited in covering nonlinear social and behavioral processes.[90,91] ST processes can be more suitably captured by an emerging group of simpler, aggregate IAMs developed with descriptive, rather than optimization-based, dynamic modeling methods. Current examples of such models include those developed with agent-based modeling (ABM) of different economic sectors[92,93] and those developed with SD modeling based on aggregate representation of cross-sectoral feedbacks.[94,95] This emerging group of models that incorporate ST processes intersects with social climate models that focus on representing human and Earth system feedbacks.[96]

These simple models represent nonlinear relationships and feedbacks, are more flexible to scope extensions compared to conventional IAMs, can be more easily calibrated to emerging data from the monitoring systems, and facilitate computational analyses with large numbers of simulations. ABMs are powerful tools for modeling social contagion and are often used with threshold models,[97] where the decision of a given actor is formulated conditional on the number of others who make that decision,[83] and hence are also used in modeling ST dynamics.[98,99] Some recent studies, though, show that threshold models may not represent the nonlinearities of real life,[55] and ABMs are often prone to stylized representations of hypothetical cases, making it sometimes hard to distil policy recommendations.[100,101] ABMs require micro-level data for calibration and validation,[100,102] and the computational requirements for micro modeling at global scale might hinder uncertainty analysis and interactive simulations.[102,103] In this regard, an aggregate modeling view, such as SD, can better suit exploring the global ST dynamics because interconnected feedbacks within and across multiple systems can be better represented in the aggregate and feedback-oriented view and the available data can be utilized at a global level. Since the complexity of micro phenomena on a global scale impedes relating model behavior to structure in ABMs,[100,104] SD models can also allow for deriving cognitively grounded insights from model output due to visual communication of the model structure with stock-flow and causal loop diagrams. Hybrid modeling approaches can also be beneficial for harnessing the advantages of different methods. In the finance context, for instance, stock-flow consistent (SFC) models[105] merge the desirable behavioral features of ABMs with robust balance sheet accounting, in which heterogeneous agents, sectors, and their financial flows are represented as a network of interconnected balance sheets, allowing for tracing of causal relations and validation of results and contributing to overcome the limitations of ABMs.

In previous global modeling studies, based on coupling social and behavioral feedback mechanisms with those of land use and climate dynamics, Eker, Reese, and Obersteiner[28] showed that triggering social norm feedbacks at an early stage of diffusion is the most influential driver of widespread shifts to plant-based diets. Moore et al.[15] presented a prominent example of cross-system modeling that found that low-emission trajectories consistent with Paris Agreement targets can emerge through positive tipping dynamics for which social conformity, technological learning, political responsiveness to public opinion, and cognitive biases in the perception of climate impacts are the key. Similar modeling studies can cover additional high-leverage systems and connections, such as energy and finance, with more nuanced and policy-relevant representation of tipping elements. Quantification of these models with globally representative data,[96] including those from the Global South and disenfranchised populations of the Global North, can help define trajectories against which actual change is monitored so that system structure and behavior can be better understood. Subsequently, this better understanding and empirical grounding enhances the usefulness of models in analyzing the effectiveness of ST interventions.

WAY FORWARD

ST points have gained wide attention in scientific and policy debates as high-leverage and cost-efficient options to accelerate

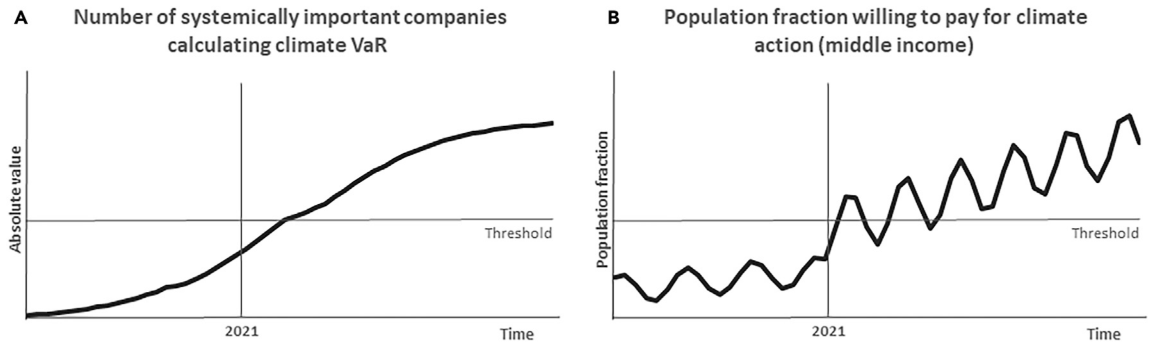

Figure 5. Stylized trajectories of monitoring variables for social tipping processes
Number of systemically important companies calculating climate value-at-risk (A) and willingness to pay for climate action (B).

emission reductions. The growing scientific literature on social (positive) tipping points over-relies on narrative accounts of ST dynamics that lack a clear empirical basis while having a narrow focus on single technologies, systems, scales, and feedback mechanisms. Harnessing the promising potential of ST dynamics, though, requires wide-ranging and systematic analyses with multiple empirical methods and with a broad systems outlook that involves multiple systems, agency scales, and interconnected feedback loops.

In this article, we set out a dynamic systems approach that involves a systems outlook with positive and negative feedback loops within and across multiple systems and scales, concurrent data collection in multiple systems not only to provide empirical evidence for tipping dynamics but also to monitor them, and dynamic simulation modeling to consolidate conceptual and empirical knowledge and for *ex ante* analysis of tipping interventions. We showed examples of how interacting positive and negative feedback loops underlying potential tipping dynamics in multiple systems can be conceptualized and which agents can play a role in triggering them. We argue that it is critical to use such a systems approach to better understand ST dynamics and to ensure climate policy relevance. This approach can be improved by explicit specification of the agents who have the power to influence those feedbacks and by identifying the differences in feedback mechanisms across the Global North and the Global South, for instance, by running participatory systems mapping exercises with global representatives. Such a systems approach can help solidify the popularity of the ST concept in better-informed policies and practices.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Sibel Eker (sibel.eker@ru.nl).

Materials availability

The only unique material generated in this study are the system maps presented in Figures 3 and 4, co-developed in an expert elicitation workshop. Extended versions of these maps can be seen in the workshop report: https://pure.iiasa.ac.at/id/eprint/17955/.

Data and code availability

This paper analyzed data reported in existing literature that are all cited in the references or in the supplemental notes. The data and code used to develop Figure 2 are available on https://github.com/sibeleker/tipping_review.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.05.012.

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AUTHOR CONTRIBUTIONS

S.E. and C.W. designed and conducted the research. N.H., M.S.M., I.M., L.N., and C.Z. contributed with data and disciplinary ideas. S.E. and C.W. drafted the text and figures. All authors reviewed and edited the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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