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Criticality and critical agency in societal tipping processes towards sustainability

E. Keith Smith[1], Carl Folke[2,3,4], Niklas Kitzmann[5,6], Manjana Milkoreit[7], Per Olsson[3], Ricarda Winkelmann[5,6,8], Anne-Sophie Crépin[2,3], Christina Eder[9], Niklas Harring[10], Jobst Heitzig[5], Alexia Katsanidou[9,11], Timothy M. Lenton[12], Franz Mauelshagen[13], Kelton Minor[14], Ilona M. Otto[15], Armon Rezai[16], Jürgen Scheffran[17], Isabelle Stadelmann-Steffen[18], Rick van der Ploeg[19,20], Nico Wunderling[21], and Jonathan F. Donges[2,5]

[1]Department of Humanities, Social and Political Sciences, ETH Zürich, Zürich, Switzerland
[2]Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, Stockholm, Sweden
[3]Stockholm Resilience Centre, Stockholm University, Stockholm,Sweden
[4]Anthropocene Laboratory, The Royal Swedish Academy of Sciences, Stockholm, Sweden
[5]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany
[6]Institute for Physics and Astronomy, University of Potsdam, Potsdam, Germany
[7]Department of Sociology and Human Geography, University of Oslo, Oslo, Norway
[8]Integrative Earth System Science, Max Planck Institute of Geoanthropology, Jena, Germany
[9]GESIS Leibniz Institute for the Social Sciences, Member of the Leibniz Association, Cologne, Germany
[10]Department of Political Science, University of Gothenburg, Gothenburg, Sweden
[11]Institute of Sociology and Social Psychology, University of Cologne, Cologne, Germany
[12]Global Systems Institute, University of Exeter, Exeter, United Kingdom
[13]Department of History, Bielefeld University, Bielefeld, Germany
[14]Data Science Institute, Columbia University, New York, United States of America
[15]Wegener Center for Climate and Global Change, University of Graz, Graz, Austria
[16]Institute for the Political Economy of Public Policy, Vienna University of Economics and Business, Vienna, Austria
[17]Institute of Geography, University of Hamburg, Hamburg, Germany
[18]Institute of Political Science and Oeschger Center for Climate Change Research, University of Bern, Bern, Switzerland
[19]Department of Economics, Oxford University, Oxford, UK
[20]University of Amsterdam, Amsterdam, the Netherlands
[21]Center for Critical Computational Studies (C^3S), Goethe University, Frankfurt, Germany

Correspondence: E. Keith Smith (keith.smith@gess.ethz.ch), Jonathan Donges (donges@pik-potsdam.de)

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Abstract. Rapid societal transformations are necessary to mitigate risky anthropogenic climate change and maintain human systems within Earth's planetary boundaries. Societal tipping processes have gained attention as mechanisms towards sustainability, yet generalisable solutions for intentionally transforming societal systems remain unclear. Here, we emphasise the significance of uncovering the systemic societal conditions enabling tipping from a complex adaptive systems perspective. Building upon research on societal tipping, transitions, and transformations, we develop the concepts of *criticality* — the likelihood of societal tipping—and *critical agency* — the human capacity to shape conditions that increase or reduce systemic criticality. We identify the transformation stages of criticality as the key analytical focus, and explore the phases of enacting critical agency within the societal tipping process. Criticality can serve as a crucial compass for policymakers, entrepreneurs, and activists, and other change-makers illuminating how critical agency can be used to instigate desired 'positive' societal tipping.

1 Introduction

Accelerated sociotechnical changes are an essential dynamic of the modern world, driven by increasingly networked global societies(Steffen et al., 2015). These changes are associated with an unprecedented deterioration of Earth's planetary life support systems, including the destabilisation of the climate system and the impairment of biosphere integrity (Rockström et al., 2023). Large-scale and rapid societal transformations are necessary to mitigate dangerous future impacts of anthropogenic pressures and to reach sustainable development goals. A central challenge is the mismatch between societal timescales and Earth system responses (Winkelmann et al., 2022). Societies operate on short-term political and economic cycles, while the Earth system responds over decades or centuries. Contemporary actions (like emitting greenhousex gases) can have delayed but long-lasting effects, locking in future changes to Earth systems. This lag means that by the time impacts are fully realised, it may be too late to avoid them.

Societal tipping processes have emerged as a promising mechanism for catalysing large-scale transformation(Winkelmann et al., 2022; Farmer et al., 2019; Ginkel et al., 2020; Lenton et al., 2022; Milkoreit et al., 2018; Otto et al., 2020; Lenton et al., 2023; Olsson et al., 2004). Broadly, societal tipping is exemplified by comparably small change(s) triggering large-scale shifts between alternative trajectories of a socio-economic or social-ecological system. These dynamics are typically driven by reinforcing feedbacks, such as norm shifts, social contagions, movements, innovation, institution building, and cross-scale transitions(Winkelmann et al., 2022; Milkoreit et al., 2018; Otto et al., 2020). Tipping has been framed in both positive terms (e.g., rapid decarbonisation)(Lenton et al., 2022, 2023) and negative terms (e.g., polarisation, financial collapse, conflict)(McLeman, 2018; Spaiser et al., 2023; Scheffran et al., 2023).

However, despite growing enthusiasm, many current approaches to societal tipping remain conceptually limited. They often assume linear or deterministic pathways (panaceas, blueprints, or best practices), while overlooking the complexity, open-endedness, and inherent unpredictability of transformative social change (Winkelmann et al., 2022; Kopp et al., 2025b; Olsson and Moore, 2024a; Milkoreit, 2023; Stadelmann-Steffen et al., 2021; Kopp et al., 2025a; Smith et al., 2025b). In practice, social systems are adaptive, nonlinear, and shaped by contingent, context-specific dynamics. In addition, social systems are

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inherently complex and often unpredictable. Presuming that a targeted intervention or manipulation can be controlled towards the desired outcome is a potentially very risky assumption (Milkoreit, 2023). Consequently, a more grounded and empirically informed understanding is needed, one that accounts for how tipping processes emerge in complex, adaptive systems and how human agency interacts with systemic conditions.

Here we offer a new perspective on societal tipping by developing the concepts of *criticality*[1], the likelihood of societal tipping, and *critical agency*, the human capacity to shape conditions that increase or reduce systemic criticality. We conceptualise criticality as a spectrum, ranging from systems in a low-criticality state (highly resilient and unlikely to tip) to those in a high-criticality state (low resilience, "on the edge" (Moran et al., 2025), exhibiting characteristics of self-organised criticality (Bak, 1996)). In such states, even small changes can trigger large-scale shifts or path bifurcations. Drawing on empirical and theoretical insights from complex adaptive systems, sustainability transitions, resilience thinking, behavioural science, and governance research, we demonstrate how human actors can actively shape systemic criticality strategically enacting critical agency to either accelerate desired transformations or buffer against harmful ones. This perspective offers a more nuanced, agency-centred framework for understanding and guiding societal change, addressing key limitations in existing approaches, which often oversimplify complex dynamics, assume deterministic outcomes, or neglect human agency. Rather than viewing tipping points as fixed thresholds to be discovered or triggered, we propose a reframing: that tipping is a dynamic, emergent process shaped by how enabling conditions evolve and interact across scales.

1.1 Societal tipping processes for sustainability

Broadly, systemic tipping processes are a class of phenomena in which a small perturbation can push a system into a qualitatively different mode of operation, driven by self-amplifying feedbacks (Schellnhuber, 2009). Likewise, societal tipping processes occur within a social system where, under critical conditions, small changes within the system or its environment can trigger non-linear and often irreversible transformations – commonly via cascading network effects (Winkelmann et al., 2022; Milkoreit et al., 2018; Otto et al., 2020; Franzke et al., 2022) and through scaling (Moore et al., 2015; Lam et al., 2020).

Societal tipping processes can drive both desirable and undesirable transformations. Positive tipping examples include decarbonisation of energy, mobility, food, and construction systems, while negative outcomes may involve political destabilisation, forced migration, or violent conflict. Yet, the normative evaluations of these shifts can vary depending on stakeholder perspectives. Recent research has emphasised societal dynamics that might help prevent Earth system tipping points—such as energy transitions, norm shifts, consumption changes, technological innovation, and shifts in financial markets (Lenton et al., 2022; Tàbara et al., 2022).

Much of this work focusses on identifying tipping 'triggers', interventions or perturbations (e.g., policy shifts, social movements, technological breakthroughs) that initiate positive feedbacks and steer systems toward new trajectories (Farmer et al., 2019). These triggers are often relatively small in scale (e.g., behavioural changes, norm shifts, incremental policies) but generate outsized systemic impacts (Otto et al., 2020). Tipping dynamics are closely related to other sociotechnical transition mechanisms, such as niche innovations and shifting power dynamics (Avelino, 2017; Geels et al., 2017). In contrast, broader

[1]Criticality refers to the susceptibility of a system to experience tipping processes (e.g., the system's proximity to a tipping point threshold)

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top-down interventions—like carbon taxes or regulatory bans—seek large-scale transformation through direct control, rather than by amplifying endogenous feedbacks.

2 Transformation stages of societal systems

Yet, identifying generalisable mechanisms that trigger societal tipping remains challenging. Social systems exhibit greater complexity and operate on different spatial and temporal scales than climate or ecological systems (Winkelmann et al., 2022). Given the distinctive adaptive complexity of social systems (Levin et al., 2013; Schill et al., 2019) it is difficult to pinpoint single control parameters or thresholds (Smith et al., 2025b) (similar to temperature limits in climate systems (Armstrong McKay et al., 2022)). Societal systems therefore present unique challenges (Winkelmann et al., 2022), especially given the multiple, interacting, cross-scale drivers often involved (Tàbara et al., 2018).

Persistent difficulties in identifying consistent mechanisms of sociotechnical change suggest a potentially misplaced focus in current conceptualisations of societal tipping. The sustainability transitions literature commonly conceptualises transformation as a multiphase, multilevel process (Olsson et al., 2004; Folke et al., 2005; Olsson et al., 2006; Moore et al., 2014; Herrfahrdt-Pähle et al., 2020; Olsson et al., 2006; Gelcich et al., 2010). Here, we synthesise findings from such empirical studies, comparative case analyses, and modelling work to identify four key transformation stages (TS1-TS4) for societal tipping processes (see Fig. 1):

[TS1: Creating enabling conditions] Preparing the system for change by cultivating conditions that make tipping possible (e.g., building capacities, seeding alternatives, weakening incumbent structures).

[TS2: Trigger societal tipping (path bifurcation)] Seizing windows of opportunity, Acting when systemic conditions become 'ripe' to initiate change through targeted actions at sensitive intervention points.

[TS3: Accelerate path trajectory] Navigating the transition, steering the system post-tipping to reinforce desirable trajectories and avoid unintended or harmful outcomes.

[TS4: Reinforce and stabilise the trajectory of the societal tipped path trajectory] Stabilising the new path, building resilience through positive feedbacks to prevent reversion to the status quo or the emergence of other undesirable outcomes (Lenton et al., 2022; Tàbara et al., 2022; Fesenfeld et al., 2022).

The mechanisms underlying the crucial first phase of societal tipping — creating enabling conditions — have been comparatively underdeveloped, likely due to the dominant emphasis on identifying levers and triggers for change. Yet, without the conditions that make tipping possible, even the most strategic interventions are unlikely to produce transformative outcomes. Furthermore, human agency is essential across all of these transformation stages, involving a broad mix of skills, capacities, and strategic competencies. Resilience-based approaches have often identified the importance of preparedness and readiness for rapid transitions (Olsson and Moore, 2024a; Pereira et al., 2018). They suggest that targeted interventions can be facilitated, and that if the enabling conditions are rather well-developed, tipping dynamics can potentially be triggered even without direct or targeted intervention (e.g. through events, shocks, or normal system perturbations) (Olsson and Moore, 2024a; Herrfahrdt-Pähle et al., 2020; Gelcich et al., 2010).

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Accordingly, this manuscripts establishes two essential re-conceptualisations of societal tipping processes: first, identifying a system's *criticality* as a key analytical focus; and second, understanding how critical agency can be strategically and collectively mobilised to influence systemic conditions toward — or away from — tipping.

3 Criticality as key analytical focus

'Criticality' is the susceptibility (likelihood) of a social system in a given trajectory to experience tipping processes (see Supplementary Information for definitions of key terms and formal definition of criticality). The criticality of a system increases in relation to its proximity to a tipping point or critical threshold (Bak, 1996; Moran et al., 2025), where the probability that tipping processes are triggered increases substantially. A system with high criticality is very likely to transition to alternative qualitative trajectories (Winkelmann et al., 2022; Folke et al., 2010). Criticality reflects situations where a system's resilience—its ability to persist despite change—has diminished, due to changes in underlying variables, processes, and feedbacks moving a system's dynamics closer to a threshold (Scheffer, 2009). This reflects the dynamic interactions between systemic conditions and shocks, often referred to as the interplay between slow change and abrupt change (Gunderson et al., 2022).

We argue that understanding and acting on criticality is central to navigating transformations toward sustainable futures (Westley et al., 2009; Elmqvist et al., 2019). Societal tipping processes should be understood as undergoing a path bifurcation during phases of highly critical system conditions (Fig. 1 B), where the system may shift towards alternative (more or less) stable trajectories (Elmqvist et al., 2019; Geels and Schot, 2007; Mathias et al., 2020). Unlike in common conceptualisations of tipping dynamics in the biosphere and climate (Scheffer, 2009), societal tipping towards sustainability, due higher levels of complexity (Winkelmann et al., 2022), is often not well described by the system undergoing quasi-permanent shifts to an observable alternative stable state or attractor in a closed and autonomous system (Fig. 1 C). Societal tipping is better modelled as dynamics within complex adaptive and evolving systems that are strongly intertwined with or embedded in other systems (e.g., socio-cultural, political, institutional, socio-technical). The resulting changes are rather open-ended and nondeterministic (Levin et al., 2013), which mathematically may be captured more faithfully by concepts such as pullback or snapshot attractors. Accordingly, the analytical focus of societal tipping processes should shift from identifying individual or deterministic points (e.g., triggers, interventions) towards determining how complex and embedded processes shape the criticality of a system, such that tipping becomes more likely to occur (in a rather probabilistic manner). This has been referred to as the 'adaptive dance' of slow and fast system change (Holling and Gunderson, 2002). Slower processes, such as the evolution of incentives, norms, rules, values, worldviews, power dynamics, collective actions, and corruption, gradually build or erode the system's resilience). While, faster processes, like financial crises, climate extremes, or interconnected crises (polycrises), disrupt the system and provoke sudden change.

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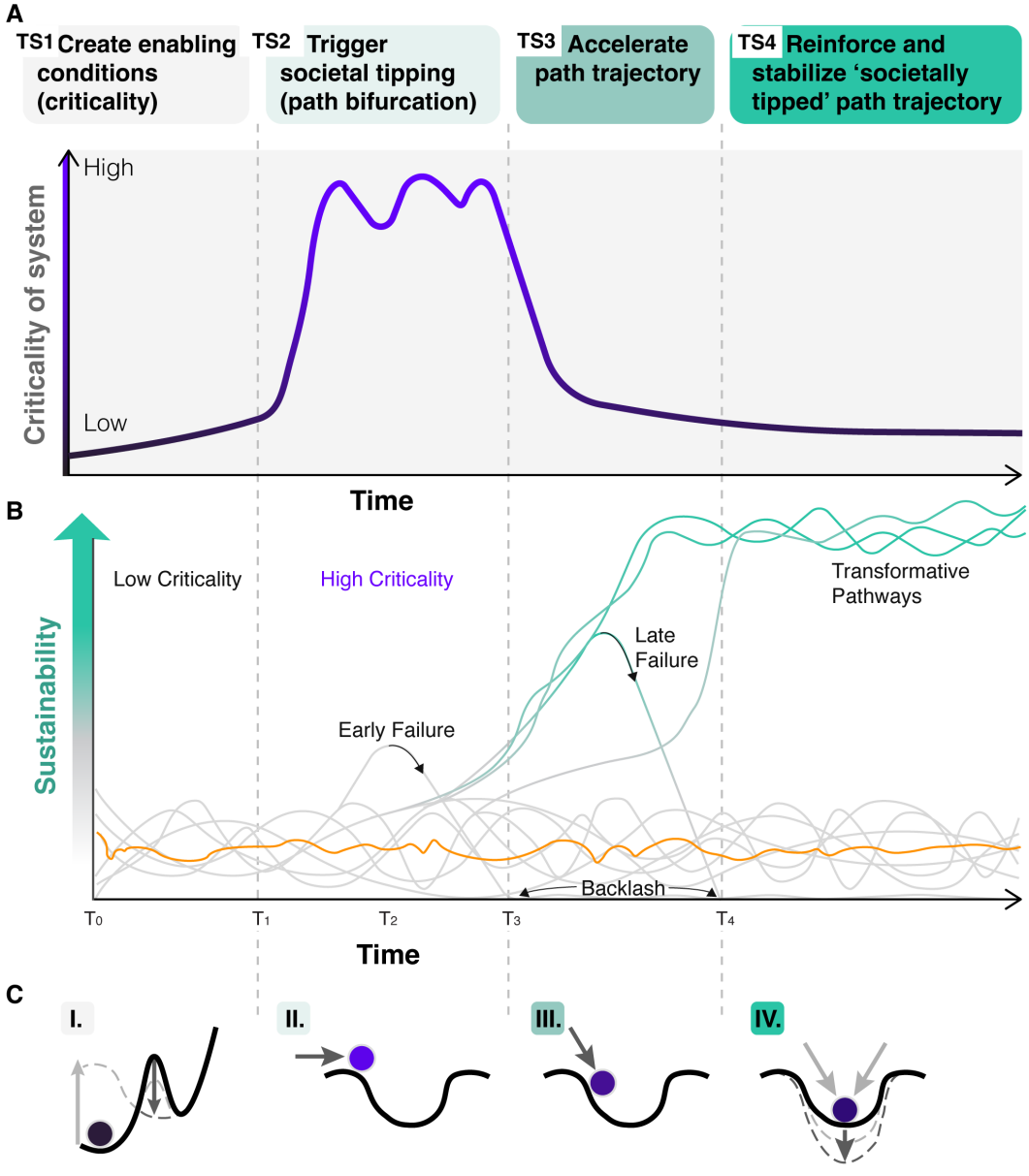

Figure 1. Transformation stages (TS) of societal system. Panel A presents the stages of unfolding societal tipping processes over time and with respect to the criticality of the system adapted (Lenton et al., 2022; Tàbara et al., 2022; Fesenfeld et al., 2022). Panel B displays the current path trajectory (in orange) alongside alternative, potential trajectories. For each of the alternative trajectories, the level of sustainability ranges from low (grey) to high (green). When the system is in high criticality, some alternative trajectories may start to diverge from the current path, but the transformation fails, either at an early or late stage. Some trajectories can be accelerated and reinforced, and emerge as a stable 'tipped' pathway. Panel C relates these phases to classical resilience-based transformation models, which are shown here as a visual metaphor adapted from (Olsson and Moore, 2024a; Olsson et al., 2004)

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Box 1: Definition of key terms

[Societal tipping processes] 'Societal tipping processes' can occur within a social system, where under critical conditions, small changes within the system or its environment can trigger larger-scale, non-linear and often irreversible transformations – commonly via network effects and positive feedbacks Winkelmann et al. (2022). Societal tipping processes can lead to both desired ("positive") and undesired ("negative") changes. In this perspective, we focus on conditions within macro-level societal systems, such as political, economic, institutional, technological, social and cultural systems that enable societal tipping processes to emerge.

[Sustainable transformation] Transformations to sustainable and equitable futures involve fundamental shifts in (i) how authority, power, and resources are structured and flow, (ii) the behaviours, practices and processes that reflect and reproduce those structures; the norms, values, and (iii) the beliefs that underpin those structures and processes and how these are connected to ecological systems across multiple scales Folke et al. (2009); Olsson et al. (2014). A sustainable transformation should lead to a more equitable access to resources for more diverse sets of actors, while simultaneously restoring and enhancing the resilience of ecological systems.

[Criticality] 'Criticality' is the susceptibility (likelihood) of a complex adaptive and evolving social system in a given trajectory to experience tipping processes. When criticality of a system is high, e.g. close to a tipping point or critical threshold Bak (1996), the probability of tipping processes to be triggered increases substantially. A system with high criticality is likely to transition onto alternative development pathways at a path bifurcation (see (iv)) following disturbances or interventions Winkelmann et al. (2022); Folke et al. (2010). Criticality is determined by the multitude of structural and process dimensions present in a social system and is therefore applicable when one-dimensional critical threshold parameters are undefinable, unknown or unknowable. Accordingly, criticality relates to similarly concepts (such as critical fragility Moran et al. (2025)), where pressures to optimise for efficiency reduce resilience, pushing systems toward tipping thresholds with little buffer for perturbation

[Path bifurcation] When in a state of high criticality, a social system can undergo a 'path bifurcation' after which it may follow one of multiple alternative and distinct future development pathways, depending on the disturbance regime and potential targeted interventions (see Fig. 1, Panel B). Path bifurcations can be generated by dynamic processes such as bifurcation-induced, noise-induced or rate-induced tipping (Ashwin et al., 2012). The concept of path bifurcation generalises concepts of criticality and societal tipping to be applicable in complex adaptive and evolving systems, where alternative stable states or attractors do not exist, and open-ended development pathways are common.

[Critical agency] 'Critical agency' is the capacity of societal actors to strategically influence the criticality of a system Olsson et al. (2006); Turnheim and Geels (2012), which can take multiple forms. First, critical agency can be utilised to increase the criticality of a system. Second, critical agency can be exercised to increase the likelihood that a favoured alternative future development pathway emerges at a path bifurcation. Third, critical agency can be adopted to strategically remove, and undermine, the internal feedback mechanisms that reinforce and maintain the current societal system. Lastly, when the criticality of a system is high, 'critical agency' can trigger societal tipping processes.

Formal definitions that can be used for operationalizing these concepts in data analysis or modelling exercises are available in Supplementary Information.

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3.1 Criticality in natural and social systems

The concept of criticality developed here is not novel, rather adopted and developed from related fields to the setting of societal tipping. Drawing on complex systems theory (Roli et al., 2018), criticality refers to a particular 'poised' or fragile state of complex systems, where heightened levels of stress have created the potential for minor disturbances or agential interventions to trigger major qualitative changes (Scheffer, 2009). This propensity for change is due to the system's organisation that allows for the change of one element to affect others, via cascading interactions that can overcome the system's resilience. Treating criticality as a structural quality of complex systems implies that it is not a binary variable, but a matter of degree. Changes to the system's parameters, internal structures or external drivers can gradually increase or decrease criticality. These changes can appear as surprises or be actively governed.

Criticality is a widely used concept across scientific domains, including physics, chemistry, ecology, neuroscience, medicine, and the social sciences. In ecology, for instance, lake systems can collapse once a critical eutrophication threshold is crossed (Scheffer, 2009). In social networks, connectivity can reach a tipping point that enables epidemic spreading, as seen in COVID-19 (So et al., 2020). In sustainability contexts, criticality is evident in potential carbon-bubble dynamics: policy shifts, economic trends, elite cues, public discourse, and activism can collectively push the financial system toward higher criticality, prompting divestment from fossil fuels. A sharp drop in asset value could then trigger a self-reinforcing spiral, as investors rush to reduce carbon risk exposure (Otto et al., 2020). Although the drivers of criticality differ (e.g., internal nutrient cycling, travel behaviour, or political alignment), in all these cases, the term 'criticality' describes system states close to the transition between fundamentally different dynamic regimes. Societal transformations become increasingly likely, across sub-dynamics, as the system approaches critical junctures (Hacker and Pierson, 2014).

In the context of societal tipping, criticality is most directly via enabling conditions (Lenton et al., 2022), where societal systems at heightened criticality can trigger 'upward-scaling tipping cascades' (Tàbara et al., 2018; Sharpe and Lenton, 2021) by deliberately instigating transformations across temporal and spatial system boundaries (Lenton et al., 2022). This framing highlights how criticality can guide where and when to implement targeted sensitive interventions (e.g., interventions which kick or shift the system into a new state (Farmer et al., 2019)), utilise leverage points (e.g., places within a complex system where a small shift in one thing can produce big changes in everything (Meadows, 1999)), and seize windows of opportunity (e.g., temporally limited openings for entrepreneurs to advance policy agendas (Farmer et al., 2019; Kingdon, 1995).

3.2 Tools for detecting criticality

A major challenge facing proposed societal tipping mechanisms is identifying knowing when and where to intervene, as well as how to evaluate whether interventions are likely to succeed. Shifting the analytical focus from tipping points to systemic criticality offers a promising pathway. Rather than searching for potentially fixed thresholds, criticality highlights the evolving conditions that make systems more or less susceptible to tipping. Accordingly, this shift allows for adoption of established diagnostic tools that monitor systemic vulnerability across different types of social, ecological, and governance systems.

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In many systems, increasing criticality can be associated with identifiable changes in system behaviour, detectable as Early Warning Signals (EWS). One well-documented example is Critical Slowing Down (CSD): a system in a state of degrading resilience (increasing criticality) returns to equilibrium more sluggishly after a disturbance (Scheffer, 2009; Lenton, 2020). Indicators such as rising autocorrelation, variance, or flickering in time-series data can help detect this dynamic. EWS have been successfully applied to natural and ecological systems, including lake collapse, forest dieback, and shifts in climate subsystems (Scheffer, 2009; Biggs et al., 2009). Applying these tools to complex, adaptive, multi-layered and agency-rich nature of social processes (Winkelmann et al., 2022), however, presents challenges, such as in quantifying uncertainties (Boettiger and Hastings, 2012; Dakos et al., 2015), and unreliability when applied to non-equilibrium processes (Dablander et al., 2022). Furthermore historical social data (e.g., surveys, voting behaviours) presents a further barrier, lacking the granularity necessary for contemporary EWS methods.

When specific tipping mechanisms are known or suspected, simulation models can help assess system criticality. Agent-based and adaptive network models are particularly useful for exploring how criticality varies with actor attributes, network structure, and dynamic interactions (Macy and Willer, 2002; Smith et al., 2025a). These models capture processes like contagion, network reorganisation, and agent heterogeneity over time. Calibrating such models to real-world conditions remains a challenge, requiring interdisciplinary collaboration to ensure validity (Schlüter et al., 2019). Another key frontier is developing network-analytical tools to assess the criticality of real-world systems. Advancing these approaches will depend on continued interdisciplinary dialogue, particularly as transformation science evolves into a "crisis discipline" (Bak-Coleman et al., 2021).

Furthermore, understanding how criticality can be shaped, and how likely societal systems are to undergo tipping processes can also be understood from identifying historical case studies of previous, potential tipping processes (Hodbod et al., 2024). Societal tipping literature has often conceptually relied upon contagion- or diffusion-based mechanisms towards rapidly decarbonizing economies or increasing technological adoption (Olsson and Moore, 2024a). Yet, such mechanisms do not always reflect the more nuanced, non-linear approaches of transformation literatures – explicitly accounting for the complex nature of social systems which rarely exhibit deterministic or linear change (Norström et al., 2022). For example, such complexity has been explored via identifying the historical and institutional factors leading to peace building and transformative justice, conditions influencing the success of feed-in tariffs and the 'Energiewende' in Germany (Lipp, 2007). There are also a great number of case-studies and empirical work in resilience and sustainability science, ranging from local, regional, to global governance systems, that have unravelled the social dynamics behind tipping points and phase shifts (often referred to as regime shifts). Here, the interplay of four interacting features of complex adaptive social-ecological systems – critical agency, social networks, bridging organisations, and institutions – has been identified as essential for active transformations towards biosphere stewardship (Folke et al., 2005; Herrfahrdt-Pähle et al., 2020).

3.3 Network Perspectives on Criticality

Complex network approaches provide an intuitive framework for modelling social-ecological phenomena (Centola, 2021; Bodin et al., 2019; Battiston et al., 2017), such as criticality (Moran et al., 2025). Linked by personal ties, political connections, or economic interdependencies, nodes within a given network can represent a broad array of societal actors: from

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individuals to groups, companies, political institutions, and entire cities and countries. Within such statistical and modelling approaches, the actors' agency and complexity are commonly reduced to simple heuristics. Nonetheless, the network effects these models capture often describe key macroscopic attributes and processes of societal systems. Network concepts and tools have been developed in a broad array of disciplines (e.g. sociology, complex systems science, statistical physics, epidemiology), and can be adapted to illustrate non-linear societal dynamics such as the complex contagion of information, behaviours, and opinions (Centola, 2021). Examples include exponential epidemiological contagion dynamics when a virus is inserted into a network of critical connectivity, and self-organisation of networked systems towards a critical state (Brockmann, 2021). Spatial models of societal tipping can also be understood as a special case of social network models. Drawing upon these diverse literatures, we describe the criticality of societal systems from two perspectives: the network factors which influence criticality, and the respective network processes which they enable and facilitate. These perspectives are intricately linked: as there are many kinds of tipping processes on networks, 'network criticality' is not a generic measure, but must be defined relative to the specific anticipated tipping mechanism. Examples for criticality-relevant system qualities and tipping-related network processes following high criticality are visualised in Panel A and B of Fig. 2, respectively.

Factors shaping criticality from a network perspective can be broadly classified as features of the network structure and traits of the actors (Fig. 2, Panel A). For contagious spreading processes (Panel B-I), criticality depends on two key components: the topology of the network, which facilitates or inhibits transmission, and the susceptibility of agents to "infection" (e.g., individuals willing to change or vulnerable populations). Different types of contagion dynamics are influenced by different structural and actor-level conditions (Panel A-I).

In simple contagion processes, such as the spread of a virus or rumour, criticality is often increased by low network clustering or modularity (Pastor-Satorras et al., 2015), and a large number of long-ranging ties ("simple connectivity" (Guilbeault and Centola, 2021)). Other kinds of social contagion, such as those associated with beliefs, behaviours, or innovations (complex contagion), may require greater local reinforcement through strong clustering, or a high density of complex paths to reach criticality ("complex connectivity" (Lenton et al., 2022; Guilbeault and Centola, 2021)). In directed social networks, such as those formed by the 'follower relationships' of some social media platforms, network motifs (micro-structures or subgraphs, such as feed-forward loops) can be especially important (Harrigan et al., 2012). Criticality-relevant agent traits (Fig. 2, Panel A-II) include agents' heterogeneity (e.g. relating to the distribution of activation thresholds (Karsai et al., 2016)); their overall level of susceptibility (e.g. to a contagiously spreading idea or behaviour (Chung et al., 2019)), and existing knowledge, beliefs, behaviours and other individual factors which may be necessary for the tipping process.

Beyond contagion, criticality can also drive reorganisation within the network itself (Panel B-II). Besides contagion processes, critical conditions can also lead to the reorganisation of the network itself (Fig. 2, Panel B-II). An important example is network polarisation (e.g., along political frontiers (Macy et al., 2021)). Here, a critical state is reached when incompatibilities of political beliefs or behaviours become stronger than the (potential) social ties connecting agents. This can create information bubbles and echo chambers (Cinelli et al., 2021), which may even serve as early warning signals for opinion change (Phillips and Bauch, 2021). The criticality perspective also has the potential to guide future research on collapsing social cohesion (Schiefer and van der Noll, 2017), investigating the critical conditions leading to diminishing in-person contact

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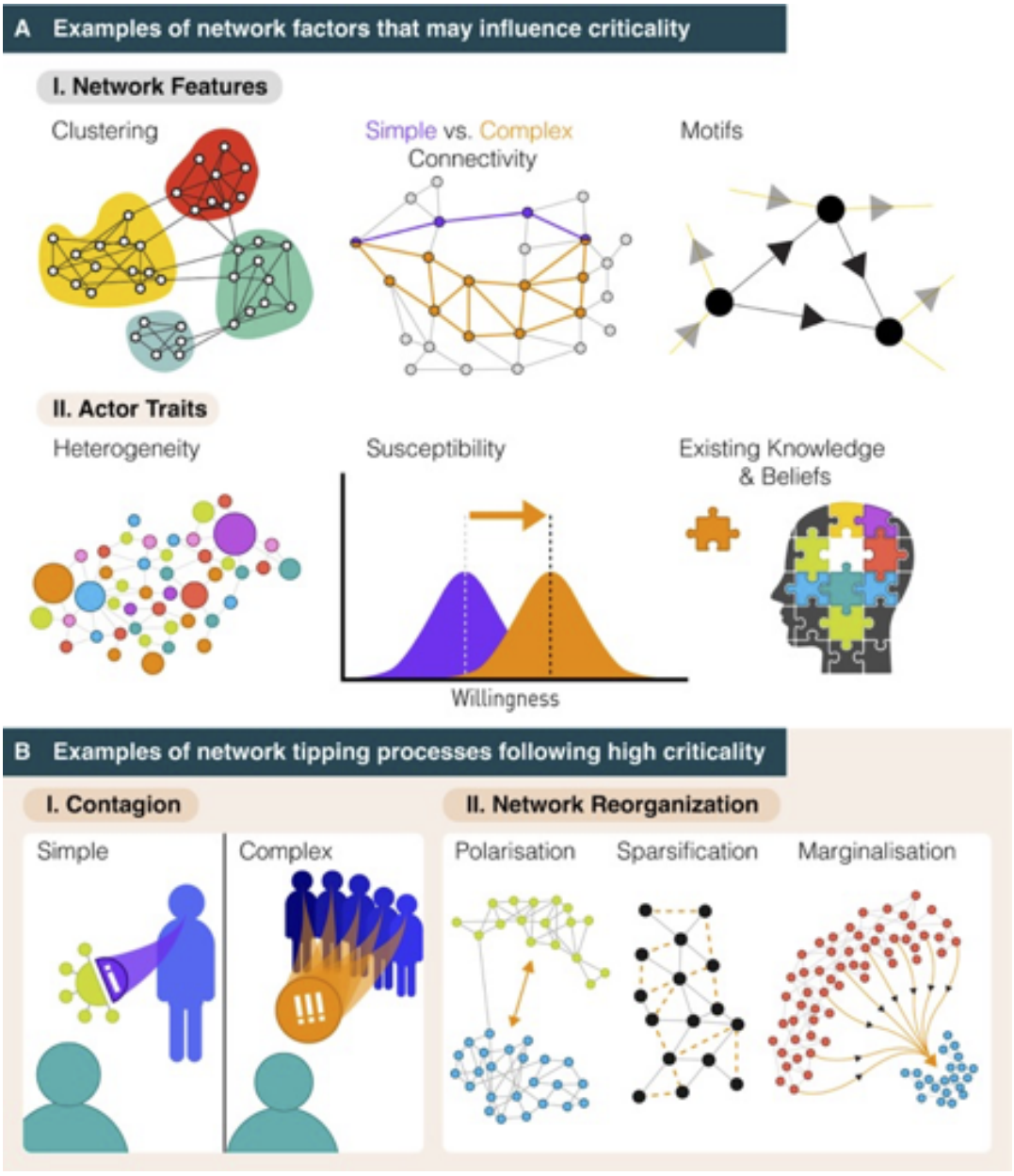

Figure 2. Criticality in social network structures and dynamics. Panel A displays examples of factors influencing criticality in a networked (social) system, relating to the network structure and the agents' attributes. Panel B presents two examples of network-related process types that may be triggered during high system criticality: contagion processes that are facilitated by the network, and re-organizations of the network structure.

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networks (sparsification) or the marginalisation of social groups. In the case of adaptive network models, with co-evolving node and network states, the division between dynamics happening *on* and *to* the network may blur, leading to more complex critical states.

4 Enacting Critical Agency for Systemic Transformation

Within dynamical systems theory, a key aspect of criticality is the absence of agency – interactions between system elements can create systemic fragility 'naturally'. Here, criticality can be self-organised (Bak, 1996) and self-reinforcing as long as the underlying mechanism(s) driving criticality remain active. However, such emergent dynamics are generally not intentional processes, but reflective of positive feedback mechanisms.

In contrast, societal transformations are rarely the product of uncontrolled external or internal forcing mechanisms. Rather, agents within societal systems exhibit consciousness, knowledge, reflexivity, and foresight (Voß et al., 2006) – the imagination and desire to intentionally transform the conditions of a system towards some desired goals. In general terms, societal transformations can be broadly understood as the co-evolution of social structures (Dobres and Robb, 2000) and agency (Giddens, 1986), where actors utilise different types of power (Bourdieu, 1989) (e.g., economic, political, symbolic) to intentionally change the societal conditions and 'rules of the game' (Herrfahrdt-Pähle et al., 2020; Williamson, 1998). A systemic transformation toward just and sustainable futures involves reshaping power structures, behaviours, and norms, guided by actors who strategically leverage agency across scales (Olsson et al., 2004; Folke et al., 2010; Westley et al., 2009; Loorbach et al., 2017).

4.1 The Dynamics of Critical Agency

'Critical agency'[2] is the intentional manipulation of the criticality of a societal system, creating the enabling systemic conditions fostering tipping processes: Hence, the focus is not just on the very tipping point itself but also on the capacities of human agency before and after the critical threshold. Critical agency is enacted by actors embedded within some "problem domain" (Trist, 1983), which are connected via being affected by a complex, societal dilemma. In this context, findings of several empirical studies have demonstrated the significance of the dynamic interplay of human agency (e.g., policy, institutional or moral entrepreneurs (Kingdon, 1995; Moore and Westley, 2011), change agents (Lenton et al., 2022), knowledge brokers (Meyer, 2010), social innovators (Westley et al., 2009), or systems entrepreneurship (Olsson, 2017)), new combinations of social networks, the emergence of bridging organizations (connecting governance levels and spatial and temporal scales), and institutions (new or existing norms and rules) in societal transformation processes (Folke et al., 2005).

However, the ways in which agency can perform in such an interplay are bounded by the structure of the system itself, where actors have differential forms and levels of agency, which can be more, or less, effective in (re-)shaping the broader conditions of a system. But the dynamic interplay of levels of agency, their networks, organizations, and institutions serve as tacit readiness, sometimes referred to as shadow networks (Olsson et al., 2006), preparing the system for transformation when

[2]The term 'critical agency' has been previously adopted within socio-cultural studies (e.g. power dynamics, international relations, critical theory). Critical agency, as defined in this manuscript, differs theoretically from these prior formulations, and should therefore not be conflated with this extant literature.

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the opportunity context of the broader conditions changes. Shocks, crises, and tipping dynamics can open space for transitioning from one system into new ones. It is during such pivotal moments of transition, or changes in opportunity contexts, when significant transformations become possible (Olsson et al., 2004; Herrfahrdt-Pähle et al., 2020; Moore et al., 2023). But these transition phases are seldom smooth and predictable. There is potential for both desirable outcomes and unwanted consequences, including periods of intense conflict and violence. The dynamics of the system are in flux and need careful navigation (Westley et al., 2013). Accordingly, agency is enacted within a constantly interactive and evolving process, sometimes slow, sometimes abrupt, of contexts shaping actions, actions reshaping the context, and the new context shaping new actions (Schill et al., 2019).

Consistent with our treatment of criticality, and going beyond rational agent perspectives, critical agency should be embedded in a complex adaptive systems perspective of human behaviour, where actions are 'enculturated' and 'enearthed' (Schill et al., 2019). Human actions are embedded and co-evolve within socio-cultural and biophysical contexts. Critical agency can be enacted to shape and re-shape societal structures across multiple levels and scales, yet these interactions are embedded (endogenised) within the given context of the structure itself. Accordingly, critical agency is a rather 'strategic' form of agency, where actions taken by multiple actors across various locations, levels, and time horizons shape the system's conditions throughout the phases of transformation (Westley et al., 2013). However, the diversity of actors—with differing preferences and expectations—can effect heterogeneous, or undesired effects. Strategic mistakes, or conflicting actions, may lead to counteracting dynamics, creating emergent patterns that may or may not ultimately drive the system toward criticality.

Understanding critical agency in transformation goes beyond a focus on the individual triggers of change, to unravelling the capacities of human agency, whether individual or collective, for confronting path-dependencies and reducing resilience of malfunctioning systems, and for nurturing and navigating the emergence of novel systems and shift towards sustainable pathways and build resilience of those (Elmqvist et al., 2019).

4.2 Phases of enacting critical agency

Research on transformations as multi-level and multi-phase processes has led to the development of analytical and intervention frameworks for transforming societal systems (Olsson et al., 2004; Herrfahrdt-Pähle et al., 2020; Geels and Schot, 2007) providing a deeper understanding of the role of agency in these processes (Moore et al., 2014; Olsson et al., 2014). This includes understanding the role of agency in both the 'unmaking' or phasing-out of existing systems, as well as the 'making' or building-up of new systems during transformations (Moore et al., 2023; Feola et al., 2021). Building upon these insights, we demonstrate how 'critical agency' can be enacted in five primary phases (CA1-CA5) to shape the criticality of a system:

[CA1] Orchestrating multiple actors and actions to increase the criticality of the societal system (such that it is likely to tip).

[CA2] Imagining and developing desired alternative trajectories under which the societal system will undergo the transformation processes.

[CA3] Decreasing the resilience of existing societal trajectories, such that bifurcations towards a desired alternative trajectory becomes more likely

[CA4] Utilising agency as an intervention to trigger a societal tipping process

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[CA5] Fostering and stabilising preferred future system trajectories. During a transformation or tipping process, the phases of critical agency can overlap or be enacted at the same time.

We map the phases of critical agency to the transformation stages in Table 1.

4.2.1 Creating enabling conditions within an untipped state

The first set of phases of enacting critical agency (CA1-CA3) target altering the dynamics of the overall societal system (e.g., norms, behaviours, structures), to change the criticality of the system.These initial phases are part of preparing the system for change (Olsson et al., 2004) and creating enabling conditions of the societal tipping process (TS1). This includes experimenting with new governance modes, building niches as protected spaces for innovation, and establishing readiness for rapid transition and tipping (Herrfahrdt-Pähle et al., 2020).

Within the first phase (CA1), pre-transformative processes involve initial societal disruptions that can be unintentional (e.g., natural disaster, pandemics, or economic shocks) (Herrfahrdt-Pähle et al., 2020; Moore et al., 2023) or organised (e.g., social movement actions) (Moore et al., 2014), and undermine the stability of a system (Olsson and Moore, 2024a; Olsson et al., 2006; Turnheim and Geels, 2012), increasing its criticality. These disruptions exhibit the potential vulnerability of system trajectories to transform, and illuminate strategic opportunities for further actors to intervene (Westley et al., 2013).

While in phase (CA2), actors need to make preparations for systemic transformations (Olsson et al., 2004). Such processes first involve sensemaking regarding the current state of the system and its problems, mapping how and what can be changed within the system (Moore et al., 2012), and the creation of a ‘common story’ (Staggenborg, 2016), which can activate further like-minded actors. Sensemaking as a form of system diagnosis and creating collective motivations for change has to be accompanied by activities that create a shared vision of a more desirable system trajectory (Wyborn et al., 2020). Shared ideas about possible (imagined) future system states and how those could be achieved (pathway imagination) are needed to direct the change process. Sustainability science has described this as visioning (Wiek and Iwaniec, 2014), imagination (Milkoreit, 2017), or anticipation (Tavory and Eliasoph, 2013), often operationalised through participatory processes like workshops to align actors’ future thinking. Yet imaginaries can also emerge from everyday individual or organisational actions—such as speaking, writing, or creating art—without coordination (Moore and Milkoreit, 2020). Yet transitions can also result in unintended or harmful outcomes, which must be anticipated and addressed.

Lastly, withinn phase (CA3), further actions are needed to undermine the mechanisms which reinforce and maintain societal systems. Societal structures (e.g., institutions, policies, norms, built environments) are often developed to be resilient, with the ultimate goal of maintaining and reproducing current ways of doing, making many societal systems quite inert and resistant to change. Targeted, strategic actions are necessary to increase the criticality of these systems, and increase the likelihood of achieving path bifurcations, including concepts such as destabilization policies (Turnheim and Geels, 2012), bifurcation policies (Olsson and Folke, 2001), and agential leadership (Folke et al., 2005). The temporal ordering of phases CA1-CA3 is not inherently fixed, in many cases, it remains likely that imagining alternative trajectories could precede pre-tipping disruptions.

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4.2.2 Triggering and navigating the transition

Within the second set of phases (CA4-CA5), critical agency is enacted when the system is in a highly critical state to initiate tipping, and importantly, to then decrease the criticality of the system, such that the new, desired trajectory is further stabilised. Accordingly, the second set of enacting critical agency phases more directly relates to the dynamics beginning at a path bifurcation (TS2). Phase (CA4), also referred to "navigating the transition" phase in a resilience-based approach to transformations (Olsson et al., 2004) or the "take-off/acceleration" phase in the transition management literature (Geels and Schot, 2007), involves enacting critical agency to intentionally trigger tipping processes – such as directed interventions to push the system onto a particular, desired new path trajectory (Farmer et al., 2019). Key capacities in this phase include evaluating and institutionalising new governance modes, making sense of changing conditions, and adapting existing institutions (institutional bricolage), while also addressing the legacies of past regimes (Herrfahrdt-Pähle et al., 2020) and managing transformation backlash (Olsson and Moore, 2024a). Recent research has documented conflict, violent resistance, and political polarisation in response to transformative change, suggesting that backlash can emerge not only during transitions but even when tipping potential becomes visible (Olsson et al., 2004; Olsson and Moore, 2024b). This adds to the uncertainty of this phase, and understanding how to navigate such turbulence remains an underexplored area in transformation and tipping research.

Lastly, in phase (CA5), after the system has passed the path bifurcation, critical agency is utilised to foster and support preferred ('desired') systemic trajectories, referred to as the "building resilience of the new trajectory" phase (Olsson et al., 2004). Here, the new trajectory can be rather fragile, and prone towards reverting towards the previous state. Critical agency is utilised to *reduce* the criticality of the system, making it more resilient. Such actions involve consolidating and strengthening new values and perceptions, implementing and enforcing new rules and regulations, making new practices and behaviours into routines (Moore et al., 2014; Herrfahrdt-Pähle et al., 2020).

Resilience-based approaches to transformations further highlight three issues that actors will need to navigate when utilizing critical agency to shape tipping dynamics: i) agency is distributed and no single actor or agent alone can likely control a complex system or tipping dynamics, ii) transformation is a nonlinear process that involves more than diffusion of specific technologies, behaviours or practices, and iii) tipping dynamics will lead to emergence, but will also be subject to crisis, disruption, and surprise as these are key features of change processes in any complex system (Olsson and Moore, 2024a). Further, drawing upon networked perspectives on criticality, if the underlying network processes and structures are known or suspected, critical agency can be enacted more effectively. For example, a given budget for disseminating a new innovation can be used more efficiently, if the nodes with the highest contagion potential can be identified and targeted (Guilbeault and Centola, 2021). Research on modelling societal system criticality, as well as effective data collection and analysis, thus takes an important role in guiding real-world agents' efforts to identify and enact their critical agency.

4.3 Exemplifying Criticality of Societal Tipping Processes

Taken together, this perspective is synthesised in Figure 3, visualising how the phases of critical agency can be enacted to influence systemic criticality at different transformation stages. The grey lines represent potential path trajectories for a societal

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Table 1. Mapping phases of enacting critical agency and transformation stages of tipping processes in societal systems

Phases of critical agency	CA1. Orchestrating pre-tipping disruptions	CA2. Imagining and developing alternative trajectories	CA3. Decreasing the resilience of current societal trajectories	CA4. Triggering societal tipping processes	CA5. Reinforce preferred development trajectories
Transformation stages of societal system (see Fig. 1)	TS1. Creating enabling conditions (criticality)			TS2. Trigger societal tipping (path bifurcation)	TS3. Accelerate path trajectory; TS4. Reinforce and stabilise 'societally tipped' path trajectories
Actions	Raise awareness, initial activism, identify and increase weaknesses in societal system, develop disruptive technologies	Niche-building and devise ideal-type for new system states, strategise and develop coalitions, goal-setting	Suppress or reduce processes and structures that stabilise and reinforce societal system	Identify sensitive intervention points, design and implement targeted interventions, institutionalise alternatives (from niches) and mitigate backlash	Develop incentives, infrastructure, governance schemes to support new trajectory
Goals	Illustrate vulnerability of system, illuminate strategic opportunities	Motivate actors and resources, expand perceptions of what can be	Make alternative trajectories more attractive	Instigate tipping processes	Increase attraction of alternative trajectory, stabilise system
Criticality	Low	Increasing	Increasing	High	Decreasing
System state	Untipped	Untipped	Untipped	Tipping	Tipped

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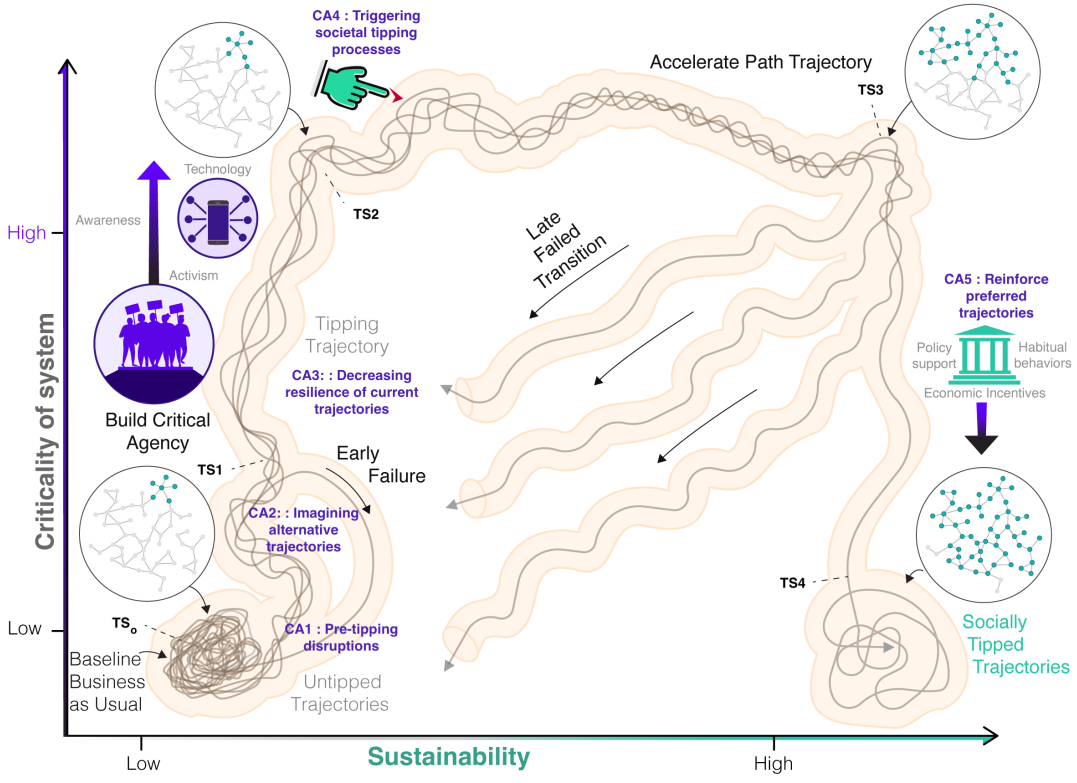

Figure 3. Criticality and critical agency in societal systems with potential for emerging tipping processes. This displays potential alternative path trajectories for a system, at different transformation stages (TS) which are instigated and supported by the phases of critical agency (CA).At low levels of criticality, the potential path trajectories for the system will remain largely stable (TS_0). Criticality can be incrementally increased by enacting phases of critical agency. These process can, for example, be driven by a contagion-like spreading process on a social-ecological network (see insets), or by societal actions and technological developments (CA1-3). Some trajectories will suffer 'early failure', and return to a stable, untipped state. When a system is in a highly critical state (TS2), the tipping process can be triggered (CA4), accelerating the path trajectory towards increased sustainability of the system (TS3). Trajectories that are insufficiently reinforced (CA5) can suffer 'late' failed transitions. While trajectories that are sufficiently reinforced experience reduced criticality, and develop into stable, socially tipped states (TS4). See Table 1 for further explanation of the criticality, transformation stages, and the phases of enacting critical agency.

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system over time. In the 'baseline' state (TS0), the path trajectories remain relatively static, fluctuating around low levels of sustainability and criticality, illustrating a business-as-usual scenario where systemic transformations are unlikely.

At the first transformation stage (TS1), critical agency can be enacted through pre-tipping disruptions (CA1) and by imagining alternative trajectories (CA2). These actions initiate a departure from the status quo, seeding ideas, and reshaping conditions for change. Such agency may involve destabilising dominant regimes, creating space for alternatives, or articulating compelling visions of the future. This phase also includes decreasing the resilience of existing trajectories (CA3), for example, through shifting public narratives, building activist pressure, introducing novel technologies, or changing key economic and institutional parameters. These efforts enact critical agency to increase the system's criticality, pushing it closer to a potential bifurcation point.

However, not all emergent path trajectories will succeed in reaching and maintaining a transformed system state of higher sustainability. Some may lose momentum or face resistance, leading to an 'early failure' that returns the system's trajectory to the baseline state. This illustrates that building criticality is necessary but not sufficient for transformation.

At the second transformation stage (TS2), the system is in a high-criticality state fragile, nonlinear, and sensitive to perturbations. As the system is now highly susceptible to transformation, critical agency can be strategically enacted to trigger social tipping dynamics (CA4). This can involve implementing targeted inventions at sensitive (leverage) points within the system that are more likely to institute transformations. Such interventions could be, for example, economic (e.g., introducing a market-disrupting technology), political (e.g., enacting a bold policy shift), or sociocultural (e.g., launching a narrative campaign that shifts collective norms). In some cases, tipping can even be instigated by external shocks outside of such strategic interventions (e.g., natural disasters, pandemics, or geopolitical crises). Targeted interventions can involve the implementation of imagined and strategised alternatives (CA2). However, it is important that such interventions are well-timed and introduced when the system has a high state of criticality (closer to a path bifurcation), increasing the likelihood that such a perturbation (e.g. external event, targeted intervention) places the system on a qualitatively different ('socially tipped') trajectory. Once tipping is underway, the system enters (TS3), a phase of accelerating transformation. Sustainability increases rapidly as emerging structures and behavioural changes gain momentum. System-level changes can become more visible, as the system reorganises around new principles, actors, and relationships.

Yet even after tipping, the path trajectories remain vulnerable, as the system's criticality remains high. Reinforcing preferred alternative path trajectories is essential, otherwise the trajectory could experience 'late failed' transitions, reverting to the baseline state. Here, critical agency (CA5) can create policy structures that reify and stabilise the new trajectories, or economic incentives that reduce criticality and make the path trajectory more resilient. If successful, these actions consolidate the transformation, allowing the system to arrive at a socially tipped trajectory (TS4).

5 Societal implications for navigating criticality

Understanding criticality and societal tipping processes is key in orchestrating rapid, large-scale, and deep transformation. Critical agency is important in developing the capacity to instigate and navigate such a change. Criticality provides an important

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perspective for emerging research efforts on intentional and rapid tipping of societal systems towards sustainable futures (Rockström et al., 2023). Improved understanding of criticality in relation to tipping points can serve as a compass for policymakers, entrepreneurs, and activists, illuminating how critical agency can be incentivised to instigate desired 'positive' societal tipping (Lenton et al., 2022; Olsson and Moore, 2024a; Tàbara et al., 2018; Sharpe and Lenton, 2021). Particularly, research has focused on governance solutions towards sustainable transitions (Milkoreit et al., 2024), for example identifying policy interventions which shape the systemic enabling conditions (Fesenfeld et al., 2022), shifting previously inelastic systems away from carbon locked-in trajectories towards low-emissions pathways, or unravelling the complex interplay of the social dimensions underlying transformations towards biosphere stewardship (Olsson et al., 2004; Folke et al., 2005; Moore et al., 2014). Further, criticality relates to anticipatory governance (Muiderman et al., 2020) approaches towards sustainability challenges.

Societal tipping processes have received increased focus from civil society organisations (e.g., Dutch Social Tipping Coalitie), environmental activists (e.g., Extinction Rebellion, Last Generation) and public policy outreach efforts (Meldrum et al., 2023). Yet, societal tipping is inherently risky (Milkoreit, 2023). Tipping processes do not necessarily lead to transformations with the desired equity and sustainability outcomes (Olsson and Moore, 2024b). Societal changes are often not easily manipulated, nor can they be intentionally controlled (Milkoreit, 2023). Societal institutions and political systems are often structured to maintain social solidarity and consistency across geography and time. Breaking down the mechanisms that reinforce systemic inertia is often a prerequisite to transformative change – yet processes undermining systemic stability can have unintended consequences, such as triggering unintended changes, or even cascading risks. Destabilisation and undermining processes as part of the 'preparation phase' can be very dangerous to change agents that work to challenge and change systems, especially if they target authoritative and oppressive systems (Olsson and Moore, 2024a). The lack of capacities to deal with transformation backlash is a primary cause of why many well-intended initiatives fail. Even small, targeted, nudging interventions intended to initiate contagions of sustainable behavioural change can have unintended consequences (Zorell, 2020). Consequently, enacting critical agency to increase the criticality of a system is an action that should be taken with great caution and care, to facilitate emerging dynamics that are inclusive, legitimised, mindful of minority interests, and to be prepared for unintended consequences (where possible).

Transformative frameworks can be strategically leveraged to undermine sustainability, rather than advance it. The second Trump administration, building on decades of strategic and coordinated action (McCright and Dunlap, 2003; Farrell, 2016), has exercised critical agency to disrupt governance institutions, build alternative narratives, and weaken the resilience of existing democratic and environmental protections (aligning with early-stage tipping activities, CA1–CA3). These efforts have likely increased the criticality of the US political system, heightening its susceptibility to systemic transformations. The current implementation of long-developed plans to restructure the federal government by dismantling regulatory institutions and centralising executive power (such as those aligned with Project 2025 (Shao et al., 2025)) well exemplifies how critical agency can be strategically exercised. Whether these disruptions will result in tipping-like dynamics, whether those emerging alternative path trajectories will be stabilised or fail, and what such actions mean for the future of sustainability remains largely uncertain. Accordingly, it remains likely that the system is currently in a rather early transformation stage, where the enaction of critical agency could either foster new alternative trajectories, or even instigate backlash (such as geo-political realignments) or

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unintended consequences (e.g., shifting domestic elections in Australia and Canada towards left-leaning governments (Stevis-Gridneff, 2025)).

Inequalities in the ability to exert critical agency persist both across and within locales. More open governance systems enable a greater diversity of actors to influence systemic conditions. However, the level of agency an actor can exercise within a given context largely depends on their ability to mobilise and organise resources through their network. Consequently, actors with comparatively less critical agency—such as individuals or outsiders—may face significant limitations in shaping systemic conditions. In contrast, those with greater resources and more extensive networked access are often better positioned to enact critical agency.

Future research can leverage emerging literature on complex adaptive systems, network science, sustainability and societal transformations to derive indicators of criticality, and illuminate where critical agency efforts can be most strategically enacted. Advancing data analysis and modelling of complex contagion and social network reorganisation processes (e.g., polarisation, fragmentation, and periphery-to-core dynamics) could further highlight the criticality of societal systems (Winkelmann et al., 2022; Centola, 2021; Guilbeault and Centola, 2021). Particular focus should be placed on scrutinising temporal reorganisations of social networks, such as how meso-scale group or motif structures form and dissolve across different timescales, conditioning criticality and complex contagions (Sekara et al., 2016). Modern machine learning and data analysis approaches can be used to classify critical conditions and complex contagion processes in social networks (Kitzmann et al., 2022; Murphy et al., 2021). Further, adopting quasi-natural experiments can help evaluate targeted critical agency interventions (e.g., via public policy, market-based mechanisms, technological changes), driving development of decision support tools. Behavioural and survey-embedded experimental approaches can illuminate transformation and acceptability mechanisms (Fesenfeld et al., 2022). Social media data promises to be an especially valuable resource for future criticality research, e.g., to analyse the strength of the sentiment and the decay rate of topics in public discourse (Lenton et al., 2022).

Given the coevolution of social and ecological systems, identifying critical conditions for societal tipping processes necessitates approaches that transgress conventional disciplinary and epistemological boundaries. Accordingly, the criticality perspective presents opportunities for the development of novel, transdisciplinary research agendas, to identify conditions enabling desired sustainable, as well as mitigating unwanted, systemic transformations.

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5.2 Conflict of Interests

The authors declare no conflicts of interest

5.3 CRediT authorship contribution statement

E.K. Smith, J.F. Donges, N.H. Kitzmann, M. Milkoreit and R. Winkelmann developed the article. E.K. Smith and J.F. Donges led the writing of the manuscript, with substantial contributions from C. Folke, N.H. Kitzmann, M. Milkoreit, P. Olsson to synthesise the literature. K. Minor and N.H. Kitzmann contributed Figures 1,2 and 3. All co-authors contributed to the drafting of the paper.

5.4 Declaration of AI and AI-Assisted Technologies in the Writing Process:

The manuscript was drafted fully by the authorship team. ChatGPT was utilised for editing and clarification of sentence formulation. Authors reviewed and edited all AI-edited, and take full responsibility for the content of the manuscript.

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