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Originally published as:

[Winkelmann, R.](#), [Donges, J. F.](#), Smith, E. K., Milkoreit, M., Eder, C., [Heitzig, J.](#), Katsanidou, A., [Wiedermann, M.](#), [Wunderling, N.](#), Lenton, T. M. (2022): Social tipping processes towards climate action: A conceptual framework. - Ecological Economics, 192, 107242.

DOI: <https://doi.org/10.1016/j.ecolecon.2021.107242>

Social tipping processes towards climate action: a conceptual framework

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Abstract

Societal transformations are necessary to address critical global challenges, such as mitigation of anthropogenic climate change and reaching UN sustainable development goals. Recently, social tipping processes have received increased attention, as they present a form of social change whereby a small change can shift a sensitive social system into a qualitatively different state due to strongly self-amplifying (mathematically positive) feedback mechanisms. Social tipping processes with respect to technological and energy systems, political mobilization, financial markets and sociocultural norms and behaviors have been suggested as potential key drivers towards climate action.

Drawing from expert [insights](#) and comprehensive literature review, we develop a framework to identify and characterize social tipping processes critical to facilitating rapid social transformations. We find that social tipping processes are distinguishable from those of already more widely studied climate and ecological tipping dynamics. In particular, we identify human agency, social-institutional network structures, different spatial and temporal scales and increased complexity as key distinctive features underlying social tipping processes. Building on these characteristics, we propose a formal definition for social tipping processes and filtering criteria for those processes that could be decisive for future trajectories [towards climate action](#). We illustrate this definition with the European political system as an example of potential social tipping processes, highlighting the [prospective](#) role of the FridaysForFuture movement.

Accordingly, this [conceptual](#) framework for social tipping processes can be utilized to illuminate mechanisms for necessary transformative climate change mitigation policies and actions.

Keywords

Social tipping dynamics, social change, sustainability, critical states, network structures, FridaysForFuture

1. INTRODUCTION

2 There is a growing concern that global climate change is reaching a point where parts of the Earth System are starting to pass
3 dangerous climate tipping points (Lenton et al., 2008): In particular, a first critical threshold in West Antarctica might have
4 already been crossed, which could lead to unstable grounding line retreat in the Amundsen Basin (Favier et al., 2014; Joughin
5 et al., 2014) and in turn might trigger large-scale grounded ice loss (Joughin & Alley, 2011). Other tipping points may be
6 close: A recent systematic scan of Earth system model projections has detected a cluster of abrupt shifts between 1.5 and
7 2.0°C of global warming (Drijfhout et al., 2015), including a collapse of Labrador Sea convection with far-reaching impacts
8 on human societies. The abrupt degradation of tropical coral reefs is projected to be virtually certain if global warming
9 surpasses 2.0°C (Frieler et al., 2013; Hughes et al., 2017). Even the possibility of a global climate tipping to a ‘hothouse Earth’
10 state has been posited (Steffen et al., 2018).

11
12 Against this backdrop, there is a growing consensus not only that climate tipping points prove a salient focal point for the
13 dialogue between scientists and decision-makers (Werners et al. 2013), but also that avoiding crossing undesired climate
14 tipping points requires rapid transformational social change, which may be propelled (intentionally or unintentionally) by
15 triggering social tipping processes (Otto and Donges et al., 2020; Lenton, 2020) or “sensitive intervention points” (Farmer
16 et al., 2019; Tàbara et al., 2018). Examples for such proposed social tipping dynamics include divestment from fossil fuels in
17 financial markets, political mobilization, social norm change, and socio-technical innovation for climate change mitigation
18 and adaptation action (Lenton, 2020; Nyborg et al., 2016; Otto and Donges et al., 2020; Tàbara et al., 2018; Kwadijk et al.
19 2010; Sharpe and Lenton 2021). Equally, if human societies do not act collectively and decisively, climate change could
20 conceivably trigger undesirable social tipping processes, such as international migration bursts, food system collapse or
21 political revolutions (Kopp et al., 2016). Van Ginkel et al. (2020) distinguish and label these two kinds of social tipping
22 dynamics as social-economic ‘impact’ and ‘response’ tipping points. The underlying social tipping processes have received
23 recent attention, as they encompass the required rapid, transformational system change to combat the climate and
24 sustainability crises (Kopp et al., 2016; Lenton, 2020; Milkoreit et al., 2018; Otto and Donges et al., 2020; Sharpe and Lenton
25 2021).

26

27 Here we develop a [conceptual framework](#) for social tipping processes [with respect to both climate mitigation as well as](#)
28 [adaptation action](#). Drawing upon [a semi-structured expert process](#) and a comprehensive literature review (Sections 2 and 3),
29 we find that the mechanisms underlying social tipping processes are categorically different from other forms of tipping [in](#)
30 [climate and ecological systems, as they](#) have the capacity for agency, they operate on networked social structures, have
31 different spatial and temporal scales, and a higher degree of complexity ([Section 4](#)). Following these distinctions, we present
32 a definitional framework for identifying social tipping processes [towards climate action that builds on Milkoreit et al. \(2018\)](#)
33 [and van Ginkel et al. \(2020\)](#), where under critical conditions, a small perturbation [or intervention](#) can induce non-linear
34 systemic change, driven by positive feedback mechanisms and cascading network effects ([Section 5](#)). [The proposed](#)
35 [framework aims to establish a common terminology to avoid misconceptions, including the notions of agency, criticality as](#)
36 [well as the manifestation and intervention time horizons in the context of social tipping. In this way, the framework can serve](#)
37 [to connect literatures and science communities working on social tipping, social change, complex contagion dynamics and](#)
38 [evidence from behavioral experiments \(e.g. Centola et al., 2018; Nyborg et al., 2016\)](#). Finally, we adopt this framework to
39 understand potential social tipping dynamics in the European political system, where the *FridaysForFuture* movement
40 (Hagedorn et al., 2019) pushes the system towards criticality, generating the conditions for shifting climate policy regimes
41 into a qualitatively different state ([Section 6](#)).

42

43 **2. BACKGROUND**

44 ***2.1. Tipping points as social-ecological systems features***

45 Over the last 150 years, a suite of concepts and theories describing small changes with large systemic effects has been
46 developed at the intersection of natural and social sciences. More recently, the concepts of tipping points and tipping
47 elements have been broadly adopted by both natural and social scientists [across multiple disciplines](#). [Here, we briefly outline](#)
48 [four different scientific arenas engaged in tipping-point research, and their relationship to our own approach as proposed in](#)
49 [Section 5: \(1\) ecology and social-ecological systems research, \(2\) climate change science, \(3\) theories of social change](#)
50 [involving threshold phenomena, and \(4\) sustainability science with a focus on transitions and transformations](#).

51

52 (1) Since the mid 1990s, ecologists and social-ecological systems (SES) researchers have developed an extensive body of
53 research on tipping processes using the terminology of ‘regime shifts’ and ‘critical transitions’ (Folke et al., 2004; Walker &
54 Meyers; 2004; Scheffer, 2009; Biggs et. al. 2018). The conception of non-linear change processes in this work is strongly
55 aligned with our own: the rapid movement of a system between two clearly distinguishable stable states, e.g., a clear or turbid
56 lake, driven by positive feedback mechanisms. Recognizing the impacts of human development on various ecosystems, this
57 body of work tends to focus on regime shifts in ecosystems as a consequence of social drivers, but increasingly recognizes the
58 interaction of ecological and social causes (‘co-determinants’) of change (e.g., Lade et.al 2013; Rocha et al., 2018). Less
59 attention has been paid to sudden changes in social systems triggered by ecosystem changes.

60

61 Related to this work on the complex dynamics in coupled human-environmental systems is a rich literature on the collapse
62 of past civilizations (e.g. Butzer, 2012; Tainter, 1990) including potential tipping processes (Janssen et al., 2003). Recently,
63 Cumming and Peterson (2017) synthesized this literature with work on ecological regime shifts, proposing a ‘unifying social-
64 ecological framework’ for understanding resilience and collapse.

65

66 (2) The concept of climate tipping elements introduced by Lenton et al. (2008) and Schellnhuber (2009), has been
67 increasingly adopted within Earth and climate sciences. Climate tipping elements are defined as at least sub-continental-scale
68 components of the climate system that can undergo a qualitative change once a critical threshold in a control variable, e.g.,
69 global mean temperature, is crossed. Positive feedback mechanisms at the critical threshold drive the system’s transition from
70 a previously stable to a qualitatively different state (Lenton et al., 2008). Other scholars (e.g. Levermann et al., 2012) suggest
71 a somewhat narrower definition of climate tipping elements by introducing additional characteristics, such as (limited)
72 reversibility or abruptness.

73

74 (3) Social science theories of thresholds of change have a much longer history and are much more diverse than ecological and
75 climatic theories of tipping. Famously, Schelling (1971), following Grodzins (1957), developed a theory of tipping processes

76 to explain racial segregation in US neighbourhoods. Granovetter (1978) modeled collective behavior as a tipping process
77 dependent upon passing individual thresholds for participation in riots or protests. [Different accounts of revolutions can be](#)
78 [interpreted in terms of tipping dynamics \(e.g. Kuran 1989, Goldstone 1991\)](#), while Gould and Eldridge (1993) distinguish
79 phases of policy change and stability in terms of ‘punctuated equilibrium’ (see also [historical institutionalism, e.g., Thelen,](#)
80 [1999](#)). Gladwell (2000) popularised the concept of ‘tipping points’, exploring contagion effects (‘fads and fashions’),
81 sometimes triggered by specific events. [These diverse theories are important forerunners to theorizing about social tipping](#)
82 [points, but they differ in their approaches, and give little recognition of underlying complex-systems dynamics \(e.g., the idea](#)
83 [of alternative stable states\), network theory and the specific requirements for tipping dynamics \(e.g., positive feedback](#)
84 [dynamics as drivers of change\). They deploy different definitions, models \(e.g., cascades vs. contagion\) and ontologies.](#)

85
86 Several recent studies have examined tipping processes within contemporary social systems. Homer-Dixon (2015) and
87 Battiston et al. (2016) explored the 2008 financial crisis as a tipping phenomenon. Nyborg and colleagues (2016; 2003)
88 discussed shifts in norms and attitudes, for example regarding smoking behaviors. Centola et al. (2018) associated tipping
89 points with the ‘critical mass phenomenon’, [originally quantified by Schelling \(1971\) and Granovetter \(1978\) and](#)
90 [incorporated into diffusion of innovations theory \(Rogers 2010\)](#), wherein 20–30% of a population becoming engaged in an
91 activity can be sufficient to tip the whole society. Similarly, Rockström et al. (2017) highlighted this Pareto effect in the
92 context of decarbonization transitions. [Both Kopp et al. \(2016\) and van Ginkel et al. \(2020\) distinguished different social](#)
93 [tipping elements or social-economic tipping points that are sensitive to ‘climate-economic shocks’ or might result from](#)
94 [responses to climate change.](#)

95
96 (4) Recently, these social theories of change have become adopted to varying degrees in vibrant discussions about transitions
97 (e.g., [Geels 2002; Roberts and Geels 2019](#)), transition management (e.g., [Kemp et al 2007; van der Brugge and van Raak](#)
98 [2007](#)) and transformations (e.g., [Westley 2011, Olsson et al., 2014, Termeer et al. 2017](#)) in response to sustainability
99 challenges. This literature considers the dynamics of fundamental system reorganization – similar to the notion of moving
100 [between multiple stable states – but does not require non-linear, feedback-driven change mechanisms. Scholars acknowledge](#)

101 that transformations can be extended (multi-decadal) processes that can contain shorter periods of non-linearity (Herrfahrdt-
102 Pähle et al. 2020), but this temporal feature of tipping dynamics is not a constitutive dimension of sustainability
103 transformations. Similarly, evolutionary theories of social change (e.g., van den Bergh et al., 2019; Gavrillets and Richerson
104 2017) is not focused on the temporal aspects of change and looks at different mechanisms of change.

105

106 Milkoreit et al. (2018) reviewed the various uses of the term tipping point and related concepts, especially regime shift, critical
107 transition, and punctuated equilibrium, across these four domains, tracing their use over time. They found that the term
108 tipping point is used interchangeably or in conjunction with other concepts, especially regime shifts and critical transitions,
109 and generally refers to change phenomena with four main characteristics: multiple stable states, non-linearity, feedback
110 mechanisms and limited reversibility. Like van Ginkel et al., (2020), we build on these key characteristics of tipping for our
111 proposed framework here, engaging the growing conversation about desirable social tipping processes.

112

113 ***2.2. Social Tipping***

114 In response to the concept of climate tipping points, social scientists are re-engaging with this concept yet again, creating an
115 additional layer of tipping scholarship with an emphasis on the need for and possibility of deliberate tipping of social systems
116 onto novel development pathways towards sustainability and climate actions (e.g. Tabara et al., 2018; Westley et al., 2011).
117 Scholars argue in particular that the rapid, non-linear change of social tipping dynamics might be necessary to speed up
118 societies' responses to climate change, and to achieve the goals of the Paris Agreement. It is this element of acceleration,
119 propelled by positive feedbacks, that makes the concept of tipping particularly interesting. For example, Otto and Donges
120 et al. (2020) reported expert elicitations identifying social tipping elements relevant for driving rapid decarbonization by
121 2050. Rapid-paced changes are a distinctive feature potentially differentiating tipping dynamics from many other forms of
122 social change, including incremental (policy or institutional) changes, or more radical (socio-technical) transitions or societal
123 transformations.

124

125 Over the last decade, the literature on deliberate transitions and transformations towards sustainability has expanded
126 significantly, exploring the dynamics that lead to the reorganization of social, economic or political systems (e.g. Feola, 2015;
127 Moore et al., 2014). In many ways, this literature and the emerging work on social tipping are interested in very similar
128 phenomena: fundamental shifts in the organization of social or social-ecological systems – a movement from one stable state
129 to another – including a change in power relations, resource flows, as well as actor identities, norms and other meanings
130 (Moore et al., 2014). Transformations can be fast, but speed is generally not one of their defining characteristics.

131
132 This temporal feature of social tipping points – rapidity of change compared to the system’s normal background rate of
133 change – combined with the fact that tipping processes can be triggered by a relatively small disturbance of the system is
134 motivating scholarship on leverage or ‘sensitive intervention points’, e.g. Farmer et al. (2019), who identified such potentially
135 high-impact intervention opportunities, e.g., financial disclosure, choosing investments in technology and political
136 mobilization that may be key for triggering decarbonization transitions.

137
138 Based on a bibliometric and qualitative review of these various bodies of literature across the natural and social sciences,
139 Milkoreit et al. (2018, p. 19) proposed the following general definition of (social) tipping: “the point or threshold at which
140 small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback
141 mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible.” Milkoreit et al.
142 (2018) further noted there is a need to recognize and identify potential differences between climatic (or ecological) and social
143 tipping processes to gain a deeper understanding of these phenomena.

144

145

146 **3. RESEARCH APPROACH**

147 Given this diverse and nascent field, there is a clear need for consensus as to what defines social tipping processes, as well as
148 an understanding of how these processes are similar and diverge from dynamics in other non-social systems.

149 Here we explore the characterization of tipping processes within the natural and social sciences, examining how social and
150 climate tipping processes are differently conceptualized. We draw upon a [semi-structured](#) qualitative methodological
151 approach to illuminate these differences and key distinctions. Initially, core differences were identified and discussed [within](#)
152 [an expert workshop, consisting of a](#) selected group of 25 experts from across the climate and social sciences., [The workshop](#)
153 focused on identifying a common definition for social tipping processes, as well as the characterization of their dynamics,
154 [and was](#) convened in June 2018 in Cologne, Germany. [The workshop participants were split into cross-disciplinary breakout](#)
155 [groups, to independently identify the dynamics of social tipping processes. Then, each of these groups reported their findings](#)
156 [to the broader plenary, for discussion, consolidation, reconciliation and clarification. The process was then repeated for](#)
157 [further clarification within the breakout groups. Through this iterative inductive and deductive process, several unique](#)
158 [themes and characteristics were identified from the broader set of themes, resulting in the key differences in and definition](#)
159 [of social tipping processes presented below.](#)

160

161 Drawing upon the differences identified in this workshop, we reviewed and synthesized the emerging field of social tipping
162 processes, particularly in comparison to the related climate and ecological tipping dynamics. We then drew upon these
163 unique characteristics to develop a common definition for social tipping processes, which we explore using the example of
164 the FridaysForFuture student movement.

165

166 ***4. KEY DIFFERENCES BETWEEN SOCIAL AND CLIMATE TIPPING PROCESSES***

167 Social and climate systems' tipping processes exhibit several broad, fundamental differences in their structure and underlying
168 mechanisms: (i) agency is a main causal driver of social tipping processes, (ii) the quality of social networks and associated
169 information exchange provides for specific social change mechanisms not available in non-human systems, (iii) climate and
170 social tipping processes occur at different spatial and temporal scales, and (iv) social tipping dynamics exhibit significantly
171 more complexity than climatic ones ([see also Supplementary Information S1 for overview of proposed ordering of tipping](#)
172 [processes](#)).

173 **4.1. Agency**

174 The most important characteristic differentiating social from climate tipping processes is the *presence of agency*. While a
175 significant body of work (e.g. Nash, 2005), including Latour's actor-network theory (Latour, 2005), addresses different
176 forms and effects of non-human or more-than-human agency, here, we focus on a more narrow understanding of agency
177 that is based on consciousness and cognitive processes such as foresight, planning, normative-principled and strategic
178 thinking, that allow **individuals as well as organizations and institutions** to purposefully affect their environment on multiple
179 temporal and spatial scales. While humans have a generally poor track record of utilizing their agentic capacities especially
180 with regard to shaping the future (e.g. Bandura, 2006; European Environmental Agency, 2001; 2013), they appear unique
181 in their capacity to transcend current realities with their decisions.

182
183 Agency in this more narrow sense can be understood as the human capacity to exercise free will, to make decisions and
184 consciously chart a path of action (individually or collectively) that shapes future life events and the environment (Bandura,
185 1989). The notion of intentionality inherent in the idea of agency implies that human actors are not only able to adapt to
186 changes in their environment, but also deliberately create such changes. **Non-human life forms can also be engaged in**
187 **deliberate changes of their environment (e.g., beavers building dams), but the cognitive quality of these actions differs from**
188 **those of humans, which can be based on different forms of knowledge and meaning about the world, moral norms and**
189 **principles, or ideas about desirable futures.** Agency allows individuals, **organizations** and societies to be proactive rather than
190 merely responsive in their relationships with other humans or the environment through planning, goal setting and strategic
191 decision-making, which links decisions and behaviors in the present with consequences and realities in the (distant) future
192 (Lenton & Latour, 2018).

193
194 Governance scholars address this social-cognitive capacity for forethought and goal-pursuit in terms of anticipation (Boyd
195 et al., 2015) and imagination (Milkoreit et al., 2018), which can be tied to a set of futuring methods (Hebinck et al., 2018;
196 Pereira et al., 2018). The ability to anticipate and imagine futures enables humans and their societies (European
197 Environmental Agency, 2001: 2013) – as opposed to animal communities or ecosystems – to transcend the present and

198 shape the future according to our values and goals (Urdañ & Pajares, 2006), possibly increasing the prospects for human
199 survival in times of fast and significant environmental change (Bandura, 1989; Milkoreit, 2017). Although this ability has
200 been underutilized in the past, especially in the context of responding to climate change (Milkoreit, 2016), it is a crucial
201 dimension of the human repertoire of tools to create change and to ensure its long-term well-being.

202

203 Agency interacts with many of the additional differentiating characteristics we identify below in important ways. For
204 example, agency plays a role in the creation of social networks, institutions and meaning, i.e., the production of the structures
205 of social systems. These network structures in turn enable and constrain agency (e.g. Bourdieu & Wacquant, 1992; Giddens,
206 1990).

207

208 Physical climate tipping elements, such as ice sheets or ocean circulations, lack that ability to intentionally act and adapt.
209 However, the adaptive capacity of ecosystems can be interpreted as a form of non-human agency and learning mechanism
210 (Watson & Szathmáry, 2016, see also Supplementary Information S2). While scholarship on non-human agency, including
211 that of animals, inanimate objects, landscape features or ecosystems (e.g. Brown & Walker, 2008; Knappett & Malafouris,
212 2008) might expand our understanding of agency, the cognitive abilities that characterize human agency, especially long-
213 term, strategic thinking and a desire to adapt and change our broader environment, to our knowledge do not exist in the non-
214 human or inanimate worlds.

215 ***4.2 Social networks***

216 Understanding the *nature of social networks* is crucial for studying social tipping. While both natural (including physical and
217 ecological) and social systems can be structurally characterized as networks and studied using a network science approach
218 (Newman, 2018), social systems differ from natural systems in the quality of the networks' nodes and interconnections and
219 the processes and dynamics facilitated and impacted by these particular network characteristics. Social systems feature
220 additional network levels of information transmission (cultural and symbolic) that are largely restricted to human societies
221 compared to natural systems (Jablonka & Lamb, 2020).

222 *Network qualities unique to social systems:*

223 Networks in social and natural systems share various commonalities such as the existence of fundamental nodes and links
224 (Newman, 2018). In contrast to most natural systems, however, social networks have the capacity to intentionally generate
225 new nodes, which include socially constructed entities such as organizations and movements (Castellano et al., 2009). New
226 nodes can be created through cultural, political or legal means, as can the rules for their interactions with other existing nodes.
227 Social system nodes are unique in that they have richer cognitive realities, particularly agency and forethought. These nodes
228 often have conflicting vested interests, which may be more short-sighted than future oriented.

229 Relationships in social networks can consist of shared meanings – especially norms, identities and other ideas – and a vast
230 variety of cultural, economic and political relationships (e.g., employment, citizenship), all of which are not as pronounced
231 or non-existent in less complex human societies and nature. Hence, social network links are more diverse than links in natural
232 systems and enable different kinds of network processes. For example, links between nodes in social networks are not
233 necessarily dependent on physical co-presence, due to technologically enabled connections or the presence of more abstract
234 interrelations such as shared norms, values or interpersonal relationships.

235 *Network processes:*

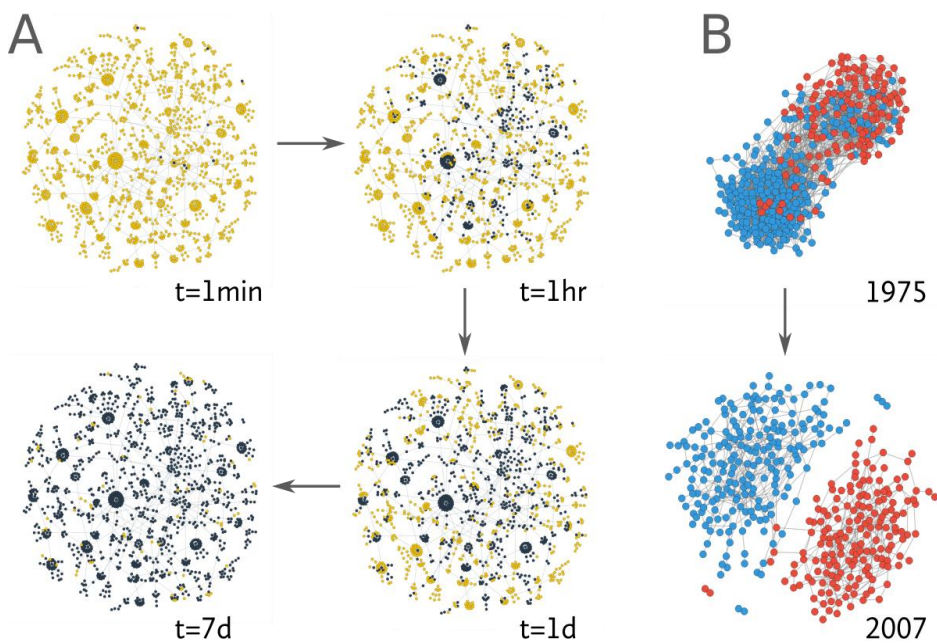
236 Social network dynamics can be of a purely ideational nature (e.g., the subject of the study of opinion and belief dynamics),
237 but also involve material changes (e.g., resource extraction, movement and transformation for economic purpose). Markets
238 are unique social networks, involving both ideational and material network processes. In the Anthropocene, the intensity
239 and speed of socially networked interaction has increased dramatically, largely due to new media, digitalization, more efficient
240 means of transportation, lower travel costs, and overall increased mobility, which is likely to increase spreading rates, while
241 at the same time affecting the stability of the network itself (Castells et al., 2006; Giddens, 2003; Harvey, 1989).

242

243 Generally, social tipping can either occur on a given network (e.g., through spreading dynamics changing the state of nodes
244 (Brockmann & Helbing, 2013) or change the network structure itself (see Figure 1). The structural network changes

245 generated by social tipping processes include transitions from centralistic or hierarchical to more polycentric (neuromorphic)
 246 structures in urban systems, energy distribution and generation networks (Kraas et al., 2016; Ostrom, 2010). Structural
 247 changes can manifest on large and small-scale spatial networks across multiple social structure levels. In order to capture these
 248 network tipping processes, quantifiers from complex network theory such as modularity, degree distribution, centrality or
 249 clustering can be used (Newman, 2018).

250



251 **Figure 1: Two types of social tipping in a complex network.** (A) Social tipping can on the one hand be
 252 characterized by a contagion process where initially only a few nodes exhibit a certain property that then
 253 spreads through a large portion of the network. (B) On the other hand, social tipping may also qualitatively
 254 alter the entire network structure from, e.g., a state with closely entangled nodes of different states to an
 255 almost or full disintegration of the network in smaller disjoint groups. The example in (A) shows the spread
 256 of an avatar among users in an online virtual world over the course of one week after it was first introduced
 257 by a small number of users (Jankowski et al., 2017). Nodes represent users and links represent the imitation
 258 of the avatar from one user to another. Yellow nodes denote users that have not picked up the avatar, while
 259 black nodes indicate those that did. (B) The upper network shows the members of the House of
 260 Representatives in the 94th United States Congress (January 3, 1975 to January 3, 1977). Node colors
 261 indicate different party membership and links between nodes are drawn if the corresponding members agree
 262 on 66% of all votes in the considered two-year period. The lower network shows the same for the 110th
 263 United States Congress (January 3, 2007, to January 3, 2009). The transition from a closely entangled to an
 264 almost fragmented topology indicates a polarisation between Democratic and Republican Party members
 265 over time (Hagedorn et al., 2019).

266

267 *4.3 Temporal and spatial scales:*

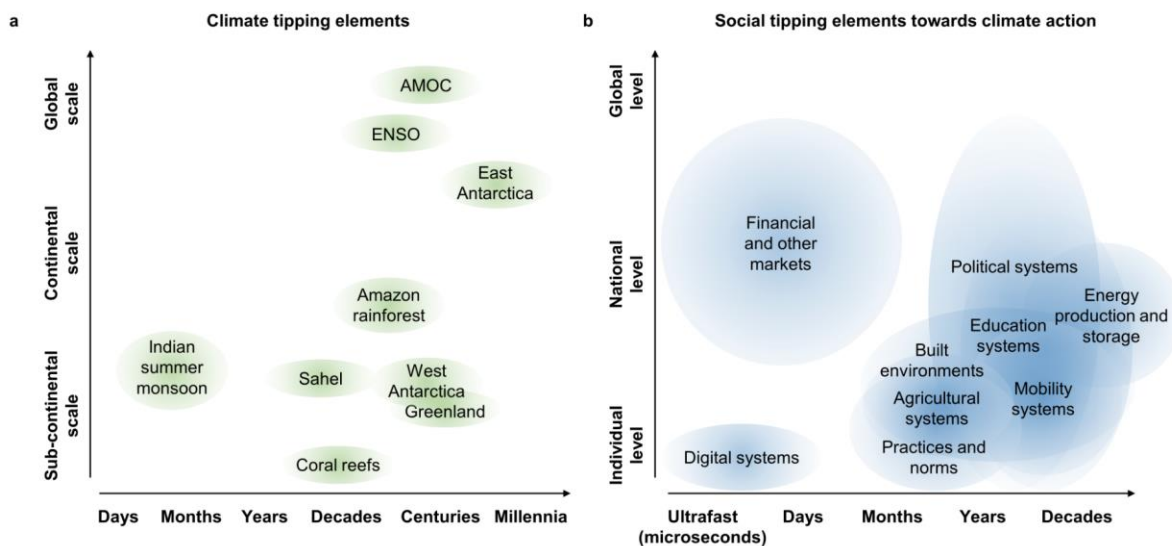
268 Scales can differ greatly between social tipping and climate tipping processes and are more ephemeral for social tipping than
269 for climate tipping (see Figure 2).

270 Overall, tipping in social systems manifests more commonly on much shorter timescales than climate tipping processes: The
271 subcontinental-scale climate tipping elements as defined by Lenton et al. (2008) have transition times of *years to millenia*,
272 where the fastest transition timescales are found for the Indian summer monsoon and Arctic summer sea-ice (on the order
273 of years to decades), and the longest ones for the ice sheets on Greenland and Antarctica (on the order of centuries to
274 millennia). Relevant timescales with respect to social tipping elements (Williamson, 1998; Otto et al., 2020; Otto and Donges
275 et al., 2020; Lenton 2020; Sharpe and Lenton 2021), on the other hand, have a comparatively shorter temporal range, from
276 ultrafast (digital and financial systems) to years and decades (political and energy systems), since longer timeframes are often
277 harder to assess (Kahan, 2017): Within social systems, fund manager performance for instance is evaluated quarterly,
278 politicians often think in electoral cycles, businesses operate with annual or five-year forecasts, while individual practices and
279 dispositions are constantly evaluated and reevaluated (Alesina et al., 1993; Dubois, 2016; Nordhaus, 1975).

280
281 Similarly, social tipping elements are often found on comparatively smaller spatial scales, commonly clustered between
282 individual and national level systems (e.g., built environments, practices and norms). While there are also many examples of
283 climate and ecological tipping elements of smaller scales (e.g., Lenton 2020), their extent is typically more clearly defined
284 (e.g., ice-covered area, or the area of a certain biome). Social scientists and economists have long grouped systems and
285 processes as existing on the macro-, meso- and micro-levels (or some variation thereof), whereby some social systems (e.g.,
286 financial markets, political systems, technologies) consist of interdependent subsystems existing on multiple spatial levels.

287
288 Social tipping processes can also display spatial-temporal *ephemerality*. While climate tipping elements have a known spatial
289 extent and dimensionality (with often a comparable extent in latitude and longitude and a generally much smaller extent in
290 altitude) and have persisted in their current stable state for thousands (if not millions) of years, social tipping processes do

291 not have a spatial extent or effective dimensionality that is known ex-ante and they can emerge (move into a critical state) and
 292 disappear (move out of a critical state) over time.
 293



294 **Figure 2: Typical spatial and temporal scales for illustrative examples of climate and social tipping elements.**
 295 Examples of climate tipping elements are broadly compiled from Lenton et al. (2008), Levermann et al. (2012), and
 296 Schellnhuber et al. (2016). Social tipping elements are broadly compiled from Kopp et al. (2016), Farmer et al. (2019), Otto
 297 and Donges et al. (2020), Hsiang et al. (2013), Tabara et al. (2018), Lenton (2020), van Ginkel et al. (2020) and Bak-Coleman
 298 et al. (2021).

300 **4.4 Complexity**

301 Social tipping processes occur in complex *adaptive* systems (Holling, 2001; Levin et al., 2013; Miller & Page, 2007). As such
 302 they can exhibit comparatively *greater complexity* in the (i) drivers, (ii) mechanisms and (iii) resulting pathways of social
 303 tipping processes, as well as the aforementioned ephemerality in their spatial-temporal manifestations, including a potentially
 304 fractal and varying dimensionality and a more complex interaction topology (Song et al., 2005, 2006). The physical climate
 305 system, by contrast, can be argued to display a lesser degree of adaptive capacity and complexity (as for instance reflected in
 306 the distinction between persistence, adaptability and transformability and their respective degrees for social-ecological

307 systems in resilience thinking, see e.g., Folke et al. (2010)). This is because, on the level of detail available for effectively
308 describing the dynamics of these systems, the fundamental laws behind the physical climate systems such as the flow of
309 glaciers or ocean currents do not change in response to forcing. In contrast in social-ecological systems, adaptation typically
310 changes system structure and functioning on the level that we have at hand for description, e.g., social-metabolic networks
311 or food webs.

312 Social tipping processes can rarely be linked to a single common control parameter, such as is the case with global mean
313 temperature in climate tipping dynamics. For most of the climate tipping elements like the ice sheets or the Atlantic
314 meridional overturning circulation, the control variables such as local air temperature, precipitation or ocean heat transport,
315 can often be translated or downscaled into changes in global mean temperature as one common driver (Lenton et al., 2008;
316 Schellnhuber, 2009). In other cases, multiple, interrelated factors are often identified as forcing the regime shifts or critical
317 transition in climatic, ecological and social-ecological systems (Scheffer et al., 2009; Hughes et al., 2013). This is clearly also
318 the case for social tipping processes: For example, shifts in social norms regarding smoking (Nyborg et al., 2016) can be linked
319 to several, entwined factors, such as policies, taxation, advertising and communication, social feedbacks (e.g., via normative
320 conformity), or individual preference changes. Centola et al. (2018) show that tipping in social convention is possibly
321 explained by a single parameter: the size of the committed minority. At larger scales, the collapse of complex civilizations has
322 been linked to multiple interacting causes, and whilst disagreement abounds over the balance of causes in particular cases,
323 there is general agreement that multiple factors were at play (Tainter, 1990). This kind of causality – multiple interacting,
324 distributed causes across varying scales – are a key characteristic of complex systems (Thurner et al., 2018), contrasting starkly
325 with conventional notions of causality involving bivariate relationships (one cause and one effect).

326
327 Further, due to their potential for agency and adaptive plasticity, social systems are open to a larger number of mechanisms
328 that could cause a tipping process and various pathways of change that a tipping process could follow towards a greater
329 number of potentially stable post-tipping states (Mathias et al., 2020). Climate tipping processes are often modeled as bi- or
330 multistable, where the directional outcomes of forcing are to some extent known or knowable, e.g., based on paleoclimatic
331 data and process-based Earth system modelling. Given a specific forcing change, one can predict in what state the element

332 will restabilize as well as the ‘net’ effects of the tipping process on larger Earth systems. Based on this understanding, the
333 tipping of climate system elements is generally perceived as undesirable and often as part of pushing the Earth system out of
334 the ‘safe operating space for humanity’ (Rockström et al., 2009; Steffen et al., 2015).

335
336 In contrast, for social systems, it is often unclear what a final stable state of the system will look like, or even whether the
337 changes resulting from a tipping process will be normatively considered ‘positive’ or ‘negative’. As Clark and Harley (2019)
338 point out, the characteristics of complex-adaptive social systems, including the diversity of actors and elements and the
339 different outcomes generated by local and global interactions, imply that the development pathways of these systems are less
340 predictable. Further, a social tipping process can generate new, and destroy existing, actor types (e.g., identities, institutions)
341 and their behaviors. Cross-scale dynamics and local differences are important to understand the emergent system structure
342 and change dynamics, but predictive capacities, e.g., regarding the timing of a social tipping point or the boundaries between
343 different stable states, do not yet exist (Clark & Harley, 2019). Hence, the term ‘managing transitions’ is less useful than the
344 idea of navigating a transformation pathway.

345
346 The political nature of social change processes (Patterson et al., 2017) – different actors within a social community pursuing
347 different, sometimes opposing, interests and visions for a reorganization of a social system while bringing to bear different
348 resources and strategies – further exacerbate this situation. Actors can deliberately generate new feedback dynamics that
349 support or slow change, even after a tipping point has been passed, and they can actively work to adjust the direction of
350 change.

351

352 **5 PROPOSED DEFINITION OF SOCIAL TIPPING PROCESSES**

353 From the discussion above, it follows that a definition of social tipping process should take a micro-perspective and
354 incorporate network effects and agency in addition to common tipping characteristics already explored in the review by
355 Milkoreit et al. (2018). It should also describe the timing aspects sufficiently well to understand possibilities for intervention,
356 similar to what Lenton et al. (Lenton et al., 2008) suggested for climate tipping elements. Hence we propose the following

357 definition of the various terms relevant for studying social tipping processes (see Supplementary Material S1 for a more
358 formal mathematical definition suggested for use in simulation modelling and data analysis that is consistent with what we
359 put forward here):

360

Definitions: A *'social system'* can be described as a network consisting of social agents (or subsystems) embedded within a social-ecological *'environment'*. Such a social system is called a *'social tipping element'* if under certain (*'critical'*) conditions, small changes in the system or its environment can lead to a qualitative (macroscopic) change, typically via cascading network effects such as complex contagion and positive feedback mechanisms. Agency is involved in moving the system towards criticality, creating small disturbances and generating network effects. By this definition, near the critical condition the stability of the social tipping element is low. The resulting *transient* change process is called the *'tipping process'*. The time it takes for this change to manifest is the *'manifestation time'*.¹

361 If a tipping element *is* already in a critical condition, where the stability of its current state is low, there may be a time window
362 during which an agential intervention might *prevent* an unwanted tipping process by moving the system into an uncritical
363 condition (see also SI text S1). Alternatively, if a tipping element *is not* already in a critical condition, there may be a time
364 window during which some intervention might move it into a critical condition in order to *bring about* a desired tipping
365 process.

366

367 The small change triggering the tipping process could be either (i) a localized modification of the network structure (e.g., a
368 change on the level of single nodes, small groups of nodes or links) or of the state of agents or subsystems, (ii) small changes
369 of macroscopic parameters or properties, or (iii) small external perturbations or shocks. We deliberately do not require the
370 trigger to be a *single* driving parameter. This is because we expect that a social tipping process could be triggered by a
371 *combination* of causes rather than a single cause. Furthermore, a social tipping element may be tipped by several *different*
372 combinations of causes. Consequently, for social tipping elements we cannot always expect at this point to identify a
373 common aggregate indicator (such as global mean temperature in the case of climatic tipping elements) and a well-defined
374 'threshold' for this indicator at which the system will tip (see also the discussion on complexity above).

¹ This is analogous to the 'transition time' in Lenton et al. (2008) . We avoid the term 'tipping *point*' in this definition since some of the literature uses it to refer to a point in time while some of the literature uses it to refer to a certain state of the system or its environment.

375

376 Note that social tipping as defined here is a unique form of social change, e.g., distinct from climate economic shocks (Kopp
377 et al., 2016) and more specific than socio-technical transitions (Geels, 2010, 2011). Further, social tipping also denotes a shift
378 to a qualitatively different state or trajectory, and as such, is different from standard business cycles or causes of seasonality.
379 As such, social tipping presents a particular process of social change, where a system undergoes a transformation from one
380 qualitatively different state to another, after being in a more critical state and affected by a potentially small triggering event.
381 Following our conceptual framework and definition, distinct stages of system development can be identified before (pre-
382 tipping stage) and after (post-tipping stage) such a perturbation or intervention triggering a social tipping process. As social
383 tipping processes can both transform a system to a qualitatively different, but quasi-stable state, or divert it on an entirely
384 novel, open-ended dynamic trajectory, it is however more difficult to generally define a development stage occurring “after”
385 a social tipping process has come to an end.

386

387 Further, we do not put forward a necessary condition on the (ir)reversibility of the social tipping process – similar to the
388 definition of climate tipping processes by Lenton et al. (2008) where (ir)reversibility is also not required. It remains largely
389 unclear as to whether social systems themselves are comparatively more or less reversible than climate systems. Clearly, once
390 an ice sheet is lost, there is little chance for it to reform on timescales relevant to current civilizations (e.g., Garbe et al., 2020).
391 But at the same time, it is also unclear whether a similar dramatic social shift, for example away from capitalist foundations
392 underlying global systems of trade, would be reversible. Historically, large social shifts (whether in terms of political, cultural,
393 or economic systems) were not cyclical (as it is equally improbable that an emergent post-capitalist economic system would
394 be akin to feudalism). Such discussions of how societies develop have been at the core of social science research for centuries
395 (i.e. Marx’s classic historical materialism, theories of socio-cultural evolution or even modern conceptualizations of
396 development theories), but common to most of these perspectives is that societies develop and move forward, that is, they
397 are somewhat irreversible.

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We propose several filtering criteria to focus on social tipping processes (i) that have the potential to be relevant **towards climate action** in future Earth system **trajectories** and (ii) where human interventions can occur within a pertinent *intervention time horizon* on the order of decades and will have consequences within **an ethical time horizon** on the order of hundreds of years.

5.1 Relevance of social tipping for climate action

We here consider social tipping processes to be relevant that have an impact on the biophysical Earth system or on macro-scale social systems, such as technological or energy systems, political mobilization, financial markets and sociocultural norms.. The qualitative change in a ‘relevant’ social tipping process significantly affects the future state of the Earth system directly or indirectly through interactions with other social tipping processes. Relevance can hence be defined in terms of impacts on biophysical Earth system properties such as global mean temperature, biosphere integrity or other planetary boundary dimensions. For example, tipping dynamics to a political system (e.g., social movements, shifting political coalitions) could result in policy regime changes, affecting substantial reductions in greenhouse gas emissions (Farmer et al., 2019; Otto and Donges et al., 2020). Furthermore, we consider social tipping processes that have relevant impacts on macro-social systems and can be triggered by changes in the same biophysical Earth systems, for example, mass migration due to climate impacts (Burke et al., 2015; Hsiang et al., 2013).

5.2 Intervention and ethical time horizons

We are interested in potential social tipping processes in which humans have the agency to substantively intervene, **for example, via technological or physical capacities of agential or structural actors, towards decreasing the likelihood of extreme weather events via mitigation efforts, or triggering socio-technological changes towards decarbonization.** We define intervention and ethical time horizons as follows:

423 ***Intervention time horizon***

424 Human agency interferes with a social tipping element, such that decisions and actions taken between now and an
425 ‘intervention time horizon’ could influence whether (or not) the system tips. We suggest considering only social tipping
426 processes with an intervention time **on the order of decades** (Otto and Donges et al., 2020), which arguably presents a
427 practical limit of human forethought (Tonn et al., 2006) and of future-oriented political agency. For example, international
428 governance efforts for global sustainability challenges, such as the **Montreal Protocol** or the Sustainable Development Goals,
429 tend to work with similar time horizons. Similarly, social tipping processes for rapid decarbonization to meet the Paris climate
430 agreement would have to be triggered within the next few years (Otto and Donges et al., 2020), with ambitious emissions
431 reduction roadmaps (Figueres et al., 2017; Rockström et al., 2017). The intervention time horizon is analogous to the
432 ‘political time horizon’ defined for climate tipping elements by Lenton et al., 2008. **Note that this is not equivalent to what**
433 **is often defined as “planning time horizon” (i.e., the time-scale over which certain impacts are anticipated to occur and are**
434 **taken into account in the planning process, as for instance defined by coastal protection stakeholders) which might be much**
435 **longer than the intervention time horizons considered here (i.e., the time remaining to induce and implement a certain**
436 **action/intervention).**

437 ***Ethical time horizon***

438 The time to observe these relevant consequences should lie within an ‘ethical time horizon’. This recognizes that
439 consequences manifesting too far in the future are not relevant to the current discourse on how contemporary societies
440 impact Earth systems. Such an ethical time horizon could consider only social tipping processes which can have relevant
441 *consequences within the next centuries* at most, corresponding to an upper life expectancy of the next generations of children
442 born.

443 6 EXAMPLE OF A POTENTIAL SOCIAL TIPPING PROCESS: EUROPEAN CLIMATE CHANGE POLICY

444 DYNAMICS EUROPE AND FRIDAYSFORFUTURE

445 Currently, international climate policies, including those of the European Union (EU) are insufficient to meet the +1.5°C
446 or +2°C goals of the Paris Agreement (Rogelj et al., 2016). While European policy makers presume to lead global mitigation
447 efforts and characterize their actions as ambitious (Parker et al., 2017; Rayner & Jordan, 2010), actual policy measures and
448 proposals have been lagging behind this aspiration (Geden, 2016). EU countries emit about a tenth of the world’s emissions,
449 and a policy change towards more rapid decarbonization would not only have significant direct impacts on the climate
450 system, but likely have indirect effects on the policies of other major emitters. But what kinds of sociopolitical processes can
451 lead to these necessary changes? Could such changes result from social tipping dynamics?

452

453 Public opinion is a crucial factor in policy formation, where the public can be understood as a “thermostat” signaling what
454 is politically feasible (Soroka & Wlezien, 2010; Wlezien, 1995). Shifts in public opinion can punctuate previously stable and
455 ‘sticky’ institutions, leading to policy change (Baumgartner & Jones, 2010). Increased activism and public concern regarding
456 climate change can generate new coalitions, or shift the priorities of existing ones (Sabatier, 1988; Weible & Sabatier, 2017).
457 Here we examine the European political system as an example of how social tipping processes could be triggered as a result
458 of large-scale public activism and social movements.

459

460 Following our definition above, the European political system can be viewed composed of networks of agents (i.e., activists,
461 decision-makers and organizations) with a range of social and political ties and is structured in nested and overlapping
462 subsystems (i.e., national group, transnational political coalitions). Viewed through the lens of social tipping, European
463 political dynamics present a ‘social system’, embedded within the broader international political and climate change
464 governance community ‘environment’. Driven by the *FridaysForFuture* movement (Hagedorn et al., 2019) (among other
465 things), a groundswell of bottom-up support for more proactive climate policies has recently developed among European
466 citizens, resulting in routine mass demonstrations and historical wins for Green parties in the 2019 European Parliamentary

467 Elections, as well as in federal elections in Austria, Belgium and Switzerland. These bottom-up movements could push the
468 European political system towards a critical ‘state’, creating the conditions for a tipping process towards radical policy
469 change, ultimately bringing European climate policy in line with the Paris Agreement. Accordingly, the European political
470 system could constitute a potential ‘social tipping element’, where, as it nears critical conditions, a small change to the system
471 or its broader environment could lead to large-scale macroscopic changes, affected by cascading network dynamics and
472 positive feedback mechanisms. Such transformations could involve establishing more aggressive mitigation strategies that
473 connect goals (such as remaining below +2°C, 50% emissions reductions by 2030, zero carbon emissions by 2050) with
474 measures and pathways that have a reasonable chance to achieve them (i.e., investment in negative emission technologies,
475 increased carbon taxation policies etc.).

476
477 The *FridaysForFuture* movement can be regarded as one such process pushing the European political system towards
478 criticality, where it becomes more likely that the system will be propelled into a qualitatively different state. The movement
479 was set off and inspired by a single Swedish high school student choosing to protest on the steps of the Riksdag for
480 meaningful climate action. Greta Thunberg’s protest quickly spread through the European social-political networks until
481 eventually more than a million students have been participating in weekly protests. These rapid spreading dynamics are
482 typical for social tipping processes and have resulted in growing bottom-up pressure on the European climate policy-makers
483 (Evensen, 2019; Hagedorn et al., 2019), creating an opening for significant policy change.

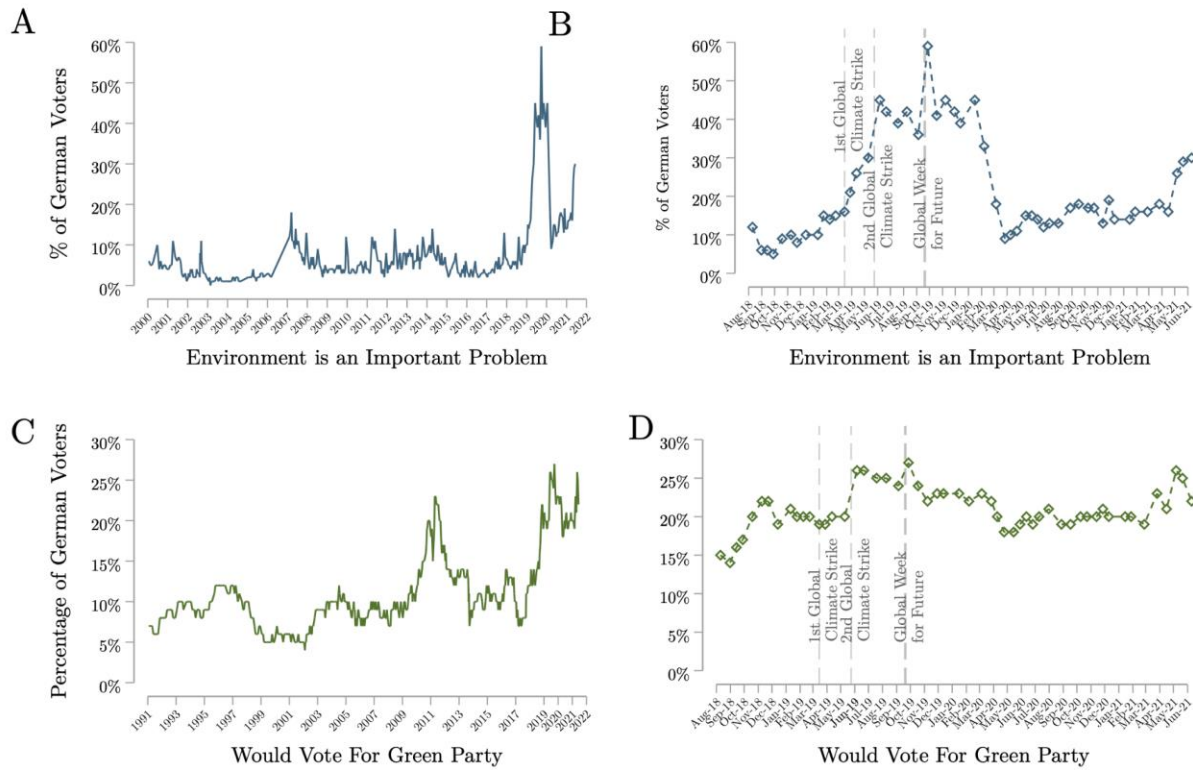
484
485 This change occurs at multiple scales in embedded subsystems within the European political system: At the national scale,
486 for example, the German socio-political system has already responded strongly to the activities of the *FridaysForFuture*
487 movement. Polling throughout 2019 in Germany suggested that the environment was the most important public policy
488 challenge, ahead of other issues, such as the migration and financial crises. Drawing upon survey data collected monthly by
489 the Politbarometer, 40–60% of Germans responded that the environment was an important problem in the Fall of 2019, a
490 rapid increase from roughly 5% in the Fall of 2018 (Figure 3, Panels A and B). In the early 2000s, rarely more than 10% of
491 Germans viewed the environment as an important problem – a time period which includes the emergence of other large

492 environmental movements in Germany, such as protests against nuclear energy in response to Fukushima. The specific
493 upward shift in Germans viewing the environment as an important problem appears to coincide with the large-scale protests
494 organized by *FridaysForFuture* in March, May and September of 2019.

495
496 At the same time, several national Western European Green Parties received strong electoral support in the May 2019
497 European Parliamentary Elections (such as in Belgium, Germany, Finland, France and Luxembourg). This increased support
498 is also reflected in polling data in Germany, where the Green Party has been effectively equal with the conservative party as
499 the preferred political party of German voters in the latter half of 2019 (Figure 3, Panels C and D). Subsequently, Germany
500 introduced its first ever federal climate change laws, mandating that the country meet its 2030 goals (a ~55% reduction in
501 GHG emissions) and establishing pathways to carbon neutrality by 2050. Currently, only a limited set of countries have
502 enacted national climate change laws, and Germany is one of the largest and most diverse economies to propose such actions.
503 This presents the possibility for policy diffusion and transfer to other states (Shipan & Volden, 2008), particularly
504 considering the influential role Germany plays within the European Union. Climate policy entrepreneurs could build upon
505 momentum to further capitalize on windows of opportunity, pushing climate change proposals prominently into national
506 and supra-national governmental agendas before the ephemeral moment passes (Kingdon, 1995).

507
508 The 2020 COVID-19 pandemic has placed new priorities on the policy agenda, also reflected in issue salience of climate
509 change (see also Fig. S1 in Supplementary Materials). As political and behavioral responses to COVID-19 have led to a
510 significant temporary reduction in greenhouse gas emissions (Le Quéré et al., 2020), this shock could be further leveraged to
511 reinforce climate action – future economic recovery packages should set European economies on a pathway towards carbon-
512 neutrality, rather than return to the old normal (Hanna et al., 2020; Rosenbloom & Markard, 2020).

513 It remains unclear whether the COVID-19 shock has supplanted climate change, or whether both remain on the political
514 agenda. For example, discussions of a “Green New Deal” remain at the core of COVID-19 economic recovery plans within
515 the European Union.



516 **Figure 3: Environment as an issue and willingness to vote for the Green Party in Germany.** Percentages of potential
 517 German voters that list the environment as an important issue for the country and willingness to vote for the Green Party
 518 (Bündnis 90/Die Grünen) if the election were to be held "today". Panels (A) and (C) present monthly survey data [from 2000](#)
 519 [to September 2020](#). Panels (B) and (D) display monthly surveys from August 2018 – September 2020, showing the change
 520 since the beginning of Greta Thunberg's protest actions. Dotted grey vertical lines display days of global strikes organized by
 521 FridaysForFuture in March, May and September 2019. Data is collected by Forschungsgruppe Wahlen: Politbarometer.
 522

523 **Implications for criticality**

524 [Drawing from our conceptual framework for social tipping, it can be assumed that the sociopolitical dynamics have likely](#)
 525 [moved the Germany political subsystem further towards criticality, but it remains largely unknown whether this will result](#)
 526 [in tipping towards a qualitatively different state, in Germany or in the broader European political system. These judgements](#)
 527 [can likely only be made in hindsight, observing whether the system remained stable, moved towards criticality or experienced](#)
 528 [tipping dynamics. Such an analysis in line with the proposed framework requires specific process tracing, identifying the key](#)
 529 [moments, actors, networks, mechanisms affecting criticality, potential thresholds, and the positive feedback dynamics](#)
 530 [propelling the system towards qualitative changes. Much attention is often paid to the specific triggering event, but it is](#)

531 rarely one single actor or action which accounts for the entirety of the tipping process. Rather a full account needs to be
532 made of all of the previous and related processes that have further placed the system towards criticality, allowing for such
533 changes to become more likely. Accordingly, for a tipping process to occur at the scale of the entire European political system,
534 moving it into a state of decarbonization that is aligned with the Paris Agreement, a series of additional social movements
535 and protests, or other shifts within the system or the environment, may be required.

536

537 Environmental social movements, such as FridaysForFuture or Extinction Rebellion, thus have the potential to accelerate
538 societal transformations (Schlosser et al, 2020) – but, common to social movements, also face several barriers to instigating
539 substantive changes. As the emergence of a social movement cannot be disembedded from the specific societal conditions
540 under which it emerged (Jenkins and Ford, 2005), and the effects of social movements may be indirect – conditioned by
541 social and political factors such as temporal and political opportunities (Kingdon, 1995; Amenta et al., 1992) – identifying
542 causality in changes resulting from social movements is particularly difficult (Giugni, 1998; Earl, 2000). Furthermore, social
543 movements can instigate different forms of success, such as public awareness and acceptability of the issue or tangible
544 developments (such as policy or behavioral changes; Gamson 1975). In this way, environmental social movements could be
545 successful in raising awareness of climate change, but often do not succeed in substantially shifting policy, as the movement
546 could suffer from cooptation as it becomes more institutionalized (Goldstone, 1980) - or are insufficient to trigger policy
547 changes on their own. Environmental movements can also lose momentum when presented with a well-organized
548 countermovement, such as in the United States in the 1990s (McCright and Dunlap, 2003). The effectiveness of social
549 movements also depends upon socio-political institutions and strategies. More open systems foster more moderate
550 movements (i.e. less confrontational and violent), as well as increase the likelihood of tangible gains (Kitschelt, 1986).
551 Further, as noted above, environmental policy regimes are particularly sticky, and resistant to change (Baumgartner and
552 Jones, 2010), but individual environmental behavioral adaptations also present several unique barriers as well (Kollmuss and
553 Agyeman, 2002) - such as overcoming existing behaviors, particularly for those that are higher cost (Diekmann and
554 Priesendorfer, 2003), and lack of perceived adaptive capacity (Mayer and Smith, 2018). Policies can also be kicked into a new

555 trajectory as a response to large-scale environmental disasters, caused for instance by extreme weather events (Ackerlof et al.,
556 2013; Zahran et al., 2006) or human error (such as the Cuyahoga River fire, Stradling and Stradling, 2008).

557

558 While we identify the role of *FridaysForFuture* in creating critical conditions, or potentially triggering the social
559 transformations required for [large-scale climate action](#), recent literature has identified further tipping candidates which could
560 have generally ‘positive’ effects on [climate mitigation and adaptation](#). For example, divestment and reinvestment present
561 candidates for rapid decarbonization and processes to achieve climate targets (Farmer et al., 2019; Otto and Donges et al.,
562 2020). In this case, intervention times range from years to decades, depending on the social structure level. [Actual examples](#)
563 [of positive tipping](#) have begun to be identified with uptake of electric vehicles in Norway and shutting down of coal power
564 generation in the UK (Sharpe and Lenton, 2021). Other studies note that the adoption of technologies and behaviors such
565 as rapid change in dietary preferences reducing meat consumption and associated land-use and climate impacts can follow
566 an epidemic-type model of diffusing across social networks (Kopp et al., 2016; Lenton, 2020).

567

568 Alternatively, social tipping processes can lead to states of criticality with less desirable outcomes: [Van Ginkel et al. \(2020\)](#)
569 [identify potential socio-economic tipping processes resulting from climate induced triggers](#), such as collapses in the
570 [agricultural sector and coastal retreat from future sea-level rise](#). Recently it has been shown that climate change has
571 contributed to the emergence of infections carried by mosquitoes, like dengue fever or Zika, which could be accelerated
572 further by increased mobility, e.g., through denser air traffic networks (Brockmann & Helbing, 2013). The thermal
573 minimum for transmission of the Zika virus could in fact give rise to a threshold behaviour (Tesla et al., 2018). Changes to
574 the local environment may enact ‘push’ factors, resulting in large-scale migrations (Jennissen, 2007; McLeman & Smit, 2006).
575 Further, increased global mean temperature has been suggested to increase the likelihood of civil conflicts (Hsiang et al.,
576 2013).

577

578 These social tipping processes are of great interest to policy makers, as it is desirable to potentially trigger or facilitate ‘positive’
579 tipping (Lenton, 2020; Tàbara et al., 2018; Sharpe and Lenton, 2021), while at the same time, mitigating the effects of
580 potential ‘negative’ outcomes.

581

582 7. DISCUSSION

583 Social tipping processes have been recognized as potentially key pathways for generating the necessary shifts [towards climate](#)
584 [action](#). Drawing upon this emerging field, this paper develops a framework for characterizing social tipping processes. We
585 find that mechanisms underlying social tipping processes are more likely to exhibit the unique characteristics of agency,
586 social-institutional and cultural network structures, they occur across different spatial and temporal scales to climate tipping,
587 and the nature of tipping can be more complex. Social tipping processes thus present qualitatively different characteristics to
588 those shared by climate tipping processes. [Accordingly, the framework developed here can serve to structure and inform](#)
589 [future data analysis and process-based modelling exercises \(Jennissen, 2007; Wiedermann et al., 2020\)](#).

590

591 [Despite the emerging focus on social tipping dynamics \(Farmer et al., 2019; Lenton, 2020; Milkoreit et al., 2018; Otto and](#)
592 [Donges et al., 2020; Tàbara et al., 2018\)](#), there remains great difficulty in [pinpointing tipping events and generalizing the](#)
593 [underlying dynamics](#). Drawing from natural tipping dynamics, previous work on social tipping has often focused on
594 identifying specific trigger events or critical thresholds in macroscopic system variables in analogy to identifying for instance
595 critical temperature thresholds in the context of climate tipping (Milkoreit et al., 2018). In natural systems the underlying
596 dynamics are more deterministic and often can be directly observed, allowing for the identification of specific thresholds [or](#)
597 [tipping points](#). In contrast, social systems comprise a much more open and complex system, one that is constantly adapting
598 and where dynamics are often incredibly complex, interrelated and cannot be directly observed. Accordingly, one could
599 observe the same event across ten similar social systems, and could potentially observe ten unique outcomes. As such,
600 anticipating a specific trigger, making causal inferences, or having generalizability in expected effects are all greatly limited
601 within social systems. Further, social tipping points are sometimes also understood as a point in time, rather than a point in

602 a complex parameter space. Such an approach makes it difficult to identify social tipping processes, as they often do not
603 contain easily observable macroscopic thresholds nor temporal markers for change.

604 Rather, a complex adaptive systems viewpoint is required, understanding the multitude of interrelated processes and social
605 structures driving change, and not focusing on a single trigger or threshold. Accordingly, our framework proposed here
606 focuses on identifying the processes and mechanisms of such change, and not a single triggering event, where the interplay
607 of micro-level changes embedded within adaptive structural conditions can affect systemic changes.

608
609 The notion of a critical state is central within our framework. Changing conditions to the system's environment can cause it
610 to enter more (or less) critical states, such that a single, or multiplicative action, can effect a systemic change. It is these
611 changing conditions, and specifically the processes and dynamics underlying them, that are of analytical importance.
612 Drawing upon the analogy of a tipping coal wagon (Kopp et al., 2016), it is not the single, specific piece of coal that caused
613 the wagon to tip, but rather the processes by which the wagon was filled with enough coal that any single piece (placed at a
614 number of different locales) could cause such tipping. Accordingly, the specific triggering event of a social tipping process
615 could be somewhat random or arbitrary, as the conditions are critical enough such that any event with enough magnitude
616 could have triggered these dynamics.

617
618 It is therefore key to focus on the processes and mechanisms underlying the nature of such critical states which allow some
619 trigger event to cause contagion dynamics or qualitative structural shifts. From social network models, we can deduce which
620 kind of structural features make a system less resilient and thus more prone to social tipping (Wiedermann et al., 2020). One
621 example is polarization, where social network models and social media-based data analyses have shown that in polarized states
622 with nearly disconnected network communities which in themselves are highly connected, contagion processes are more
623 likely to occur (Del Vicario et al., 2016; Törnberg, 2018; Vasconcelos et al., 2019). Behavioral experiments and corresponding
624 conceptual modelling approaches suggest that minority groups can initiate social change dynamics in the emergence of new
625 social conventions (Centola et al., 2018; Wiedermann et al., 2020). Furthermore, a rich social science literature has noted an
626 array of factors (i.e. political institutions, technological or behavioral adaptation, environmental, normative and attitudinal)

627 effective in shifting the social conditions surrounding climate change (Nyborg et al., 2016). A better understanding of critical
628 states as demanded by our framework may help to identify early warning signals that could possibly indicate that a social-
629 ecological system is close to a critical state in specific situations (Bauch et al., 2016; Scheffer, 2009).

630
631 Social tipping processes present a specific type of social change – **characterized** by non-linear shifting states driving by positive
632 feedbacks – which is similar to, but conceptually distinct from, other forms of social change. Similar to how we explore the
633 differences between natural and social tipping processes, further research should engage with social tipping in comparison
634 to other forms of social change (such as historical institutionalist perspectives, social movements, policy feedbacks, complex
635 systems). One of the greatest challenges lies in dealing with multiple, entangled drivers of tipping processes on different scales
636 – temporal, spatial or social structural levels – and different levels of agency and heterogeneous agents and subsystems. In
637 order to further understand the dynamics arising from these various levels of agency, it is crucial to identify examples from
638 different subfields (e.g., economics, political science, demographics).

639
640 **A key current limitation in applying our framework** is finding and operationalizing empirical data describing actual spreading
641 processes on networks across these different levels, particularly compared to macro-economic data and public opinion polls
642 (Helbing et al., 2012), even though first steps in this direction are being made (Sapiezynski et al., 2019; Sekara et al., 2016).
643 Particularly data on the social structures and networks is notoriously difficult to access. While there have been advances in
644 developing modeling frameworks (Donges et al., 2020; Wiedermann et al., 2020) to simulate social tipping dynamics, linking
645 these theoretical modelling to empirical data and behavioral experiments requires more attention. Even if predictive
646 modeling (i.e., the kind of deterministic, time-forward modeling we know from Earth System Models for instance) of such
647 social dynamics in the sense of inferring time trajectories is very difficult or even conceptually unfeasible, such process-based
648 modelling of social tipping dynamics can be very crucial to understand the nature of critical states also in real-world social
649 situations. **Lastly, we here focus specifically on social tipping processes relevant for mitigating climate change - but such a**
650 **framework for social tipping dynamics is generalizable to other areas of study and social phenomena (such as the 2020 social**
651 **movements and public opinion dynamics surrounding racial inequality in the United States).**

652

653 Our analysis of typical temporal and spatial scales of social tipping elements suggests that these commonly exist on the
654 national or sub-national level, and transitions often occur on the scale of years to decades. As such, the structure of these
655 scales are incongruent with the global threat presented by climate change, necessitating intervention on the scale of years.
656 The example of *FridaysForFuture* explored here, illustrates how a transition from the local to global spatial scale can occur.
657 The social movement further advocates for shifting intervention time horizons increasingly to the present. In this way, it
658 presents an example of potentially resolving the inconsistency between other forms of social tipping and the spatial and
659 temporal necessities of climate change mitigation. Further research is needed on the interaction of scales, both temporal and
660 spatial - for instance whether the interaction of several tipping processes on various scales might mask individual tipping
661 events.

662

663 While we explore one example of social tipping in detail, additional research is required to test the distinctiveness of social
664 tipping processes, as well as the utility of the proposed definition to other social tipping processes. Systematizing the types of
665 social tipping processes, and exemplary case studies, would help to further illustrate these forms of change. Research is also
666 warranted into further establishing the critical timescales of social tipping; understanding how network structures affect
667 social tipping dynamics; identifying typical network structures of systems entering critical states; discerning the temporal
668 aspects of how effects travel through different social network structures; and gaining a better understanding of the origin of
669 spreading processes. Sustainable behavioral adaptations co-evolve within varied cultural and biophysical contexts, and could
670 be understood from adopting complex adaptive systems approaches drawing upon multiple forms of data (Schill et al., 2019).
671 Data acquisition, analysis and process-based modelling could all play a role in this research agenda. A wealth of social media
672 data is available to study potential social tipping processes (Bak-Coleman et al., 2021) – however, this kind of data has mostly
673 yet to be adopted within the context of Earth System analysis and tipping dynamics. Some first modelling frameworks which
674 could also address social tipping for climate action have been suggested, which include a broad range of model components,
675 such as opinion formation, carbon cycle, and vegetation dynamics (Donges and Heitzig et al. 2020). Adaptive network-based
676 modelling approaches have been developed to identify thresholds for normative and behavioral shifts inclusive of the

677 coevolving dynamics of norms, behaviors and social structure (Snijders et al., 2010; Wiedermann et al., 2020). Further,
678 controlled behavioral experiments, increasingly large-scale and integrated with models of the natural, economic and social
679 environment of a social system of interest, allow to study the preconditions for the emergence of social tipping dynamics in
680 various contexts (Centola et al., 2018; Bak-Coleman et al., 2021).

681
682 In summary, our findings underline how social tipping processes become increasingly decisive for the future of the Earth
683 System in the Anthropocene: some rapid shifts in social systems are, in fact, necessary to meet the targets of the Paris
684 Agreement and the Sustainable Development Goals (Steffen et al., 2018). While we focus here on processes relevant for
685 future trajectories of the Earth system, we suggest that further analysis could use or adapt our definition to characterize other
686 types of general social tipping processes (i.e. revolutions or rapid transformations). We also recognize that tipping processes
687 within ecosystems present an interesting intermediary case between social and physical climate tipping as they typically
688 incorporate characteristics from both realms (see preliminary discussion in the SI). Understanding, identifying and
689 potentially instigating some social tipping processes is highly relevant for the future of the Anthropocene, particularly with
690 regard to the potential role in triggering rapid transformative change needed for effective Earth system stewardship (Farmer
691 et al., 2019; Lenton, 2020; Otto and Donges et al., 2020; Tàbara et al., 2018).

692 **Acknowledgments**

693 **General:** We are very grateful to William C. Clark, Anne-Sophie Crépin, Niklas Harring, Matthew Ives, J. Doyne Farmer,
694 Wolfgang Lucht, and John Schellnhuber, for providing helpful insights and comments. We thank the participants of two
695 DominoES workshops on social tipping dynamics held at GESIS Leibniz Institute for Social Science, Cologne, in summer
696 2018 and 2019 for foundational and framing discussions.

697 **Funding:** This work has been supported by the Leibniz Association (project DominoES), the Stordalen Foundation via
698 the Planetary Boundary Research Network (PB.net), the Earth League's EarthDoc programme, IRTG 1740 funded by

699 DFG and FAPESP, and the European Research Council (ERC advanced grant project ERA: Earth resilience in the
700 Anthropocene, ERC-2016-ADG-743080). R.W. acknowledges support by the Deutsche Forschungsgemeinschaft (DFG)
701 by grants WI4556/3-1 and WI4556/4-1, as well as the TiPACCs project that receives funding from the European Union's
702 Horizon 2020 Research and Innovation program under grant agreement no. 820575. T.M.L.'s contribution was
703 supported by the Leverhulme Trust (RPG-2018-046).

704

705 **Author Contributions:** Drawing upon the concepts developed in the expert elicitation workshop, R.W., J.F.D., E.K.S.,
706 M.M. and T.M.L structured the conceptualization into the resultant framework and wrote the paper with the support of
707 the co-authors. All co-authors contributed to the discussion of the manuscript. M.W. analyzed data and created Fig. 1.
708 R.W. and E.K.S. created Fig. 2. E.K.S. analyzed data and created Fig. 3. J.H. derived the mathematical definition of social
709 tipping processes (Sect. S1).

710

711 **Competing Interests:** The authors declare no competing interests.

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712 **Supplementary Materials**

713 ***SI: A mathematical definition of social tipping processes***

714 In this section, we give a more formal version of the definition of ‘social tipping process’ given in the main text, as a reference
715 for mathematically inclined readers.

716 After defining what we mean by a social system and its environment, we first classify their possible states into critical,
717 unmanageable, uncritical, and tippable conditions, and then finally define the notions of prevention time and triggering
718 time.

719 By a social system, Σ , we mean a set of agents together with a network-like social structure, that interacts in some form with
720 the rest of the world, called the environment, E , of the system, such that, if no “perturbation” or deliberate “influence” by
721 some decision-maker occurs, Σ and E together can only follow certain “quasi-inertial” (or “default”) trajectories restricted
722 by the agency of the system’s agents. Let $x_{(t)}$ and $y_{(t)}$ denote the states that Σ and E are actually in at time t .

723 A critical condition for the system is a pair of possible system and environment states, (x^*, y^*) , such that there exists another
724 possible pair of states, (x', y') , with the following properties:

725 1. The state pair (x', y') is no further away in state space from (x^*, y^*) than a certain “small” distance, ϵ , that
726 represents the possible magnitude of “local” perturbations in Σ (affecting only few agents or network links directly) or small
727 changes in E that are considered sufficiently “likely” to care about, with respect to some suitable distance function d . In
728 other words, $d((x', y'), (x^*, y^*)) < \epsilon$.

729 2. If Σ and E were in state (x', y') at any time t' , there is a quasi-inertial trajectory that would move Σ at some later
730 time $t'' > t'$ into some state x'' that is “qualitatively” different from x^* . This move represents a “global” (i.e., affecting a very
731 large fraction of the agents) and “significant” change in the system (but not necessarily in its environment).

732 If such a change actually happens, the time point t' (not the state!) at which it starts may be called the tipping point or less
733 ambiguously the triggering time point, and the system behavior within the time interval from t' to t'' is called the
734 corresponding tipping process. An uncritical condition for Σ and E then is any pair of states that is not critical.

735 A critical condition is unmanageable for an actor that may influence Σ or E in some way if there exists a possible pair of
736 states, (x', y') , with $d((x', y'), (x^*, y^*)) < \epsilon$ and the following property:

737 • Assume that Σ and E were in state (x', y') at any time t' and afterwards the state of Σ and E would follow any
738 trajectory $(x(t), y(t))_{t \geq t'}$ that the actor can force it to follow. Then the resulting trajectory would still move Σ at some time
739 $t'' > t'$ into some state x'' (which will usually depend on the influence exerted) that is qualitatively different from x^* .

740 Similarly, an uncritical condition, (x°, y°) , is tippable by a decision maker if there is a possible trajectory $(x(t), y(t))_{t \geq t'}$,
741 starting in (x°, y°) at some time t' , that the decision maker can force Σ and E to follow, and this trajectory would move Σ
742 into some state x'' at some time $t'' > t'$ that is qualitatively different from x° (a tippable uncritical state roughly corresponds
743 to what others call a ‘sensitive intervention point’).

744 At any time at which the system is not in an unmanageable critical state, the prevention time is the time interval it takes before
745 some quasi-inertial trajectory has moved it into an unmanageable critical state. In other words, at time zero it is the largest

746 time interval T so that, when no intervention takes place until time T , for all $t > 0$ with $t < T$, the system would not be in
747 an unmanageable critical state at time t .

748 Similarly, at any time at which the system is in a tippable uncritical state, the *triggering time* is the time interval it takes before
749 some quasi-inertial trajectory has moved it into an uncritical state that is no longer tippable. In other words, at time zero it is
750 the largest time interval T so that, when no intervention takes place until time T , for all $t > 0$ with $t < T$, the system would
751 not be in a tippable uncritical state at time t .

752 We only consider social tipping processes for which the prevention or triggering time is smaller than some *intervention time*
753 *horizon*.

754 ***S2 Ecosystem tipping as intermediary case***

755 Ecosystem tipping processes share properties of physical climate tipping dynamics in atmosphere, ocean and cryosphere in
756 that they can often be described by a common driver, as well as that of deliberative social tipping elements in that they have
757 adaptive capacity, and can therefore be regarded as intermediate. But, as previously noted, human agential capacity is far
758 greater than those of other species.

759 Similarly to human social systems, ecosystems are comprised of interacting living organisms, they can be viewed as networks
760 with components that can adapt (e.g., food webs). This is different from physical tipping elements such as the cryosphere
761 elements (e.g., melting of permafrost) which do not typically exhibit the same networked structures. Within the nominally
762 ‘climate’ tipping elements are some major biomes – notably boreal forests, the Amazon rainforest, and coral reefs – that are
763 composed of living organisms and exhibit ecological network structures. Indeed changing interactions between the living
764 elements of these systems may be key to tipping dynamics – for example epidemic bark beetle infestation of boreal forests
765 triggered by climate warming allowing the beetles to complete two life cycles rather than one within a season (Schuldt et al.,
766 2020). Thus these biotic tipping elements lie towards smaller scale ecosystems in the continuum, and tend to be more closely

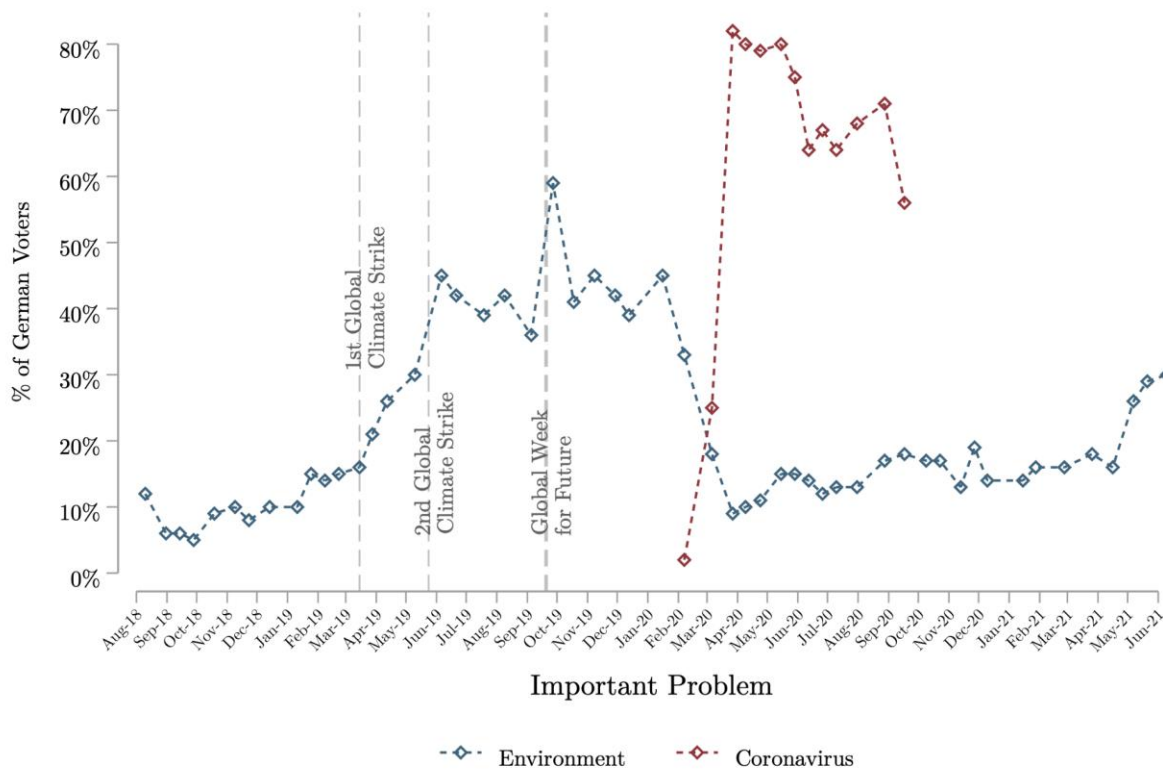
767 related to social systems in spatial and temporal scales compared to the typically much larger and more slowly changing
 768 physical climate tipping elements.

769 These differences give rise to a proposed ordering of tipping elements, ranging from (1) the physical climate tipping elements
 770 via (2) ecosystem tipping elements to (3) social tipping elements (Table S1).

771 *Table S1: Proposed ordering of tipping processes ranging from physical climate tipping processes via ecosystem*
 772 *tipping processes to social tipping processes.*

Properties	Physical climate tipping processes	Ecological tipping processes	Social tipping processes
Degree of agency	<i>Low/Absent</i>	<i>Intermediate</i>	<i>High</i>
Network structure	<i>Uncommon</i>	<i>Common</i>	<i>Common</i>
Temporal-spatial scales	<i>Slower and larger</i>	<i>Faster and smaller</i>	<i>Faster and smaller</i>
Degree of complexity	<i>Lower</i>	<i>Intermediate</i>	<i>High</i>

773 **Figure S1:**
774



775 **Figure S1: Environment and Corona as an important issue in Germany.** Percentages of potential German voters that
776 list the environment and the Coronavirus as an important issue for the country from August 2018 – June 2021, showing the change
777 since the beginning of Greta Thunberg’s protest actions. Dotted grey vertical lines display days of global strikes organized by
778 FridaysForFuture in March, May and September 2019. Data is collected by Forschungsgruppe Wahlen: Politbarometer.