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Negative Social Tipping Dynamics Resulting from and Reinforcing Earth System Destabilisation

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Abstract. In recent years research on positive social tipping dynamics in response to the climate crisis has produced invaluable insights. In contrast, relatively little attention has been given to the potentially negative social dynamics that might arise due to an increasingly destabilised Earth system, and how they might in turn reinforce social destabilisation dynamics and/or impede positive social change. In this paper, we identify potential negative tipping elements linked to Earth System destabilisation and draw on related research to understand the drivers and likelihood of these negative tipping dynamics, their potential effects on human societies and the Earth system, and the potential for cascading interactions and contribution to systemic risks. This first attempt to provide a first explorative conceptualisation of negative social tipping dynamics is intended to motivate further research into an under-researched area that is nonetheless crucial for our ability to respond to the climate crisis and for ensuring that positive social tipping dynamics are not averted by negative ones.

1 Introduction

Recent advances in research on Earth system tipping points (e.g., Armstrong McKay et al., 2022), paint an increasingly alarming picture of the state of our planetary system. Understanding tipping points and other forms of non-linear change is now widely recognised as critical to managing and responding to change in complex systems (Scheffer, 2009). We define social tipping points as critical thresholds in a social system at which a small change can trigger a significant and often irreversible phase transition in the social system because of self-amplifying, non-linear feedback(s) within the social system (Otto et al., 2020, Milkoreit 2023). Social tipping points can be both positive (predominantly beneficial to humans and the natural systems) and negative. We regard the tipping process as negative if the phase transition or the resulting newly reached equilibrium, i.e., the new state of the social system, leads to further destabilisation of the Earth system, which has potentially catastrophic consequences for human societies and ecological systems (IPCC, 2022; Lenton et al., 2023). Increasing attention is also being paid to cascade effects that connect different systems, implying that a change in one system may trigger further change in another system (Liu et al. 2023). Here, we consider a tipping cascade to take place when one tipping point triggers the crossing of another tipping point (Klose et al 2021).

Although research on the potential for positive social tipping dynamics in various systems (e.g., food, energy, transportation, financial, behavioral etc.) has started to emerge (Tàbara et al., 2018; Otto et al., 2020; Lenton 2020; Lenton et al., 2022; Winkelmann et al., 2022, Milkoreit, 2023), there has been limited research on negative social tipping dynamics that might be triggered by climate change. This is noteworthy, not least because early research on tipping points in the social sciences was mostly concerned with undesirable social processes, such as rapid and non-linear patterns of urban racial segregation in the United States (Schelling, 1978). More recently, researchers have used dynamical systems analyses to empirically study tipping points in school segregation (Spaiser et al., 2018), political instability of countries (Grimm & Schneider, 2011), and rapid proliferation of misinformation (Törnberg, 2018).

We assume that negative social tipping points are triggered unintentionally and are a result of complex, often non-linear dynamics, in line with the original social tipping points research (Schelling, 1978). Even where vested interests result in deliberate climate obstruction (Ekberg et al., 2023), we assume that large-scale negative outcomes are accepted rather than intended. The role of agency is therefore strikingly different in the conceptualisation of negative social tipping points, compared to positive social tipping points, where the assumption is that positive social tipping processes and dynamics can be steered by agents through creation of enabling conditions for positive social tipping to occurr (Alexander et al., 2022; Winkelmann et al., 2022). This notion of steering has been challenged recently (Milkoreit, 2023).

Negative and potentially catastrophic consequences are unequally distributed both internationally, as well as within each society. Research has emphasised that low-income countries that have often contributed least to the destabilisation of the Earth system, will bear the brunt of the climate change impacts (IPCC, 2022; Lenton et al., 2023). Moreover, within each society, it is the most vulnerable groups, such as children (Thiery et al., 2021; UNICEF, 2021), women (Denton, 2002), minority groups (Berberian et al., 2022, Donaghy et al., 2023) and generally the less affluent (Thomas et al., 2019), who will be most affected by climate change impacts. Triggering negative social tipping points will have considerable consequences for these vulnerable groups, further amplifying their vulnerability and stressing the need for climate justice (Newell et al., 2021).

In this perspective, we pose the following questions: (1) What are the potential negative social tipping points that the destabilisation of the Earth system could trigger? (2) How do these negative tipping elements interact and what cascades could these interactions cause? (3) To what extent could the triggering of negative social tipping points and cascades further destabilise the Earth system? And (4) what intervention options are available to prevent negative social tipping points and cascades.

2 Mapping out Negative Social Tipping

We identify five negative social tipping points that some existing evidence suggests could be triggered by Earth system destabilisation (see Figure 1). The part or subsystem of a larger system that can pass a tipping point is referred to as the tipping element. Drawing on the positive social tipping element framework developed by Otto et al. (2020), we identify four social tipping elements (TE) that have the potential for negative tipping processes (TP): socio-psychological systems (TE1), political systems (TE2), human settlements (TE3) and financial markets (TE4). Figure 1 provides an overview of these tipping elements and the tipping points that could be triggered within these tipping elements: Anomie (TP1.1), Radicalisation & Polarisation (TP1.2), Displacement (TP2.1), Conflict (TP3.1) and Financial Destabilisation (TP4.1). The figure also indicates the potential for interactions between various negative tipping elements. The interactions between different TEs indicate different possible destabilisation pathways that could lead to the crossing of negative tipping points across scales and regions. This illustrative selection is based on evidence for tipping processes in these subsystems and evidence that Earth system destabilisation has a direct effect on these subsystems.

[FIGURE 1 HERE]

2.1 Anomie

The concept of anomie, which was introduced by Durkheim (1893, 1897) to describe the breakdown of norms and social order and its relationship to suicide patterns in societies, has evolved over decades of social research (Abrutyn, 2019; Twyman-Ghoshal, 2021). We define anomie as a state of a society or community that is characterised by a breakdown of social norms, social ties and social reality, resulting in social disorder and disorganisation, disorientation, and disconnection. These syndromes manifest on the individual level through mental health deterioration, increased suicide rates, and/or increased deviant behaviour (Brown, 2022; Teymoori, Bastian & Jetten, 2017). Although this is a relatively new area of research, there is increasing evidence to suggest that changes in the Earth System can contribute to anomie. For instance, anomie has been observed in the aftermath of natural disasters, made more likely by climate change (Miller, 2016) and it has been suggested that Earth System destabilisation may result in a new form of anomie, called environmental anomie (Brown, 2022), where sudden changes to the physical landscape can upend the established social order and undermine people's ability to comprehend, relate to, and function within their environment. Beyond anomie resulting from extreme weather events caused by escalating climate change, there is also evidence for a rise in anomic experiences, particularly by young people and children around the world, contributing to a mental health crisis. In a first comprehensive study, surveying 10,000 children and young people (aged 16-25 years) in 10 countries (Australia, Brazil, Finland, France, India, Nigeria, Philippines, Portugal, UK and USA) Hickman et al. (2021) found that more than 45% said their feelings about climate change negatively affected their daily life and functioning, 75% reported that they find the future frightening, and 83% said they think people (adults) have failed to take care of the planet. For a summary of other studies, see Figure 2.

[FIGURE 2 HERE]

The extent of tipping dynamics in anomie have not yet been studied directly, but some studies have demonstrated tipping dynamics in phenomena that can serve as proxies for the anomic state of a society or community. Specifically, (complex) contagion processes have been observed for mental disorders and distress, including suicide (Scatà et al., 2018; Paz, 2022), for deviant behaviours (Busching and Krahé, 2018), and for distrust (Ross et al., 2022). Anomie tipping can also result from a single extreme event, for instance, triggered by an Earth system tipping point being breached. Such an event can instantly disintegrate whole communities, scattering members of the community in the aftermath (i.e., interaction with displacement), often leaving them with depleted social and mental resources (Miller, 2016) and establishing the perception that society as a whole is failing (Teymoori et al., 2017). Tipping in this case can be described using Logistic Map models (Bruun et al., 2017). Anomie can have feedback effects on the Earth system, further destabilising it through various pathways. When social norms disintegrate, certain pro-social behaviours and collective action that are necessary to slow down the climate crisis may diminish (Constantino et al., 2022; Schneider and van der Linden, 2023; Lettinga et al., 2020). Without strong social norms supporting collective action and fostering trust and cooperation, it becomes increasingly challenging to implement effective measures to address accelerating Earth system destabilisation, hence increasing the likelihood for Earth system tipping (Fehr et al., 2002; Thøgersen, 2008; Malerba, 2022).

2.2 Radicalisation & Polarization

Radicalisation can be a reaction to perceived external threats, including ecological threats. Research suggests that people can respond to climate change and other ecological threats by becoming more authoritarian and derogative against outgroups

(Fritsche et al., 2012; Jackson et al., 2019; Taylor, 2019; Russo et al., 2020; Uenal et al., 2021). This effect can be further exacerbated by the well documented effect of heat on aggressive behaviours, including online hate speech (Stechemesser et al., 2022). While current trends seem to suggest increasing polarization (Dunlap et al., 2016, Vihma et al., 2021, Cole et al., 2023), as climate change progresses and becomes a more concrete existential threat throughout the world (Huggel et al., 2022), we may see even socially liberal individuals developing increasingly authoritarian and reactionary views (Gadarian, 2010; Hetherington & Suhay, 2011; Huddy & Feldmann, 2011). Radicalisation can exhibit tipping dynamics. Research has described radicalisation, e.g., the spread of right-wing ideology (Youngblood, 2020), through complex contagion processes (Centola et al., 2018). Similarly, the spreading of extremist content on social media has been observed to follow complex contagion processes (Ferrara, 2017). Moreover, processes of "cross-pollination" of radical ideas have been documented (Kimmel, 2018; Baele et al., 2023), including for climate denial (Agius et al., 2020). And political polarization tipping, often accompanying radicalisation of certain segments of the population, has been found to be difficult to reverse due to asymmetric self-perpetuating trajectories (Macy et al., 2021).

Radicalisation and polarisation can have feedback effects on the Earth's System, destabilising it further. According to research (Stanley et al., 2017; Stanley & Wilson, 2019; Julhä & Hellmer, 2020), authoritarian and social dominance attitudes are negatively related to environmental attitudes and support for environmental/climate change policies. Indeed, right-wing ideology has been repeatedly correlated with climate change denial (Hornsey et.al, 2016; Hoffarth & Hodson, 2016; Czarnek et al., 2020; Julhä & Hellmer, 2020). When climate is denied, no attempts are made to mitigate climate change, on the contrary, decisions may be taken to further prop up high-emitting industries (Ekberg et al., 2023; Darian-Smith, 2023). There is however increasingly a retreat of pure climate denial (primary climate obstruction), instead we see a rise in secondary and tertiary climate obstruction, which can include deliberate polarisation of societies on the issue (Kousser & Trantr, 2018, Goldberg & Vandenberg, 2019; Mann, 2021; Flores et al., 2022, Ekberg et al., 2023).

2.3 Displacement

Acute and slow-onset environmental pressures, such as extreme weather events and sea level rise (e.g. due to the melting of the West Antarctic Ice Sheet), are projected to impact the migration (voluntary) and displacement (forced, involuntary) of a large proportion of the population. As the proportion of the global population living in coastal regions continues to grow, likely surpassing one billion people this century, sea-level rise is projected to be one of the most costly and irreversible consequences of climate change (Hauer et al., 2019, McLeman, 2018, Kaczan & Orgill-Meyer, 2020). As global tipping points are reached, the increase in rapid-onset hazards and sea level rise is likely to increase pulse-like migration and displacement events (McLeman, 2018). Displacement can happen suddenly and is characterised by amplifying or positive feedbacks that can increase and maintain displacement even after the extreme weather event or initial shock has passed. This in turn can make those communities inhospitable for displaced populations to return to, creating a cycle that reinforces, extends, or renders the displacement permanent. Displaced populations must grapple with the loss of their livelihoods, often by identifying new temporary sources of income that can become permanent due to the challenges of returning to origin communities (Young & Jacobsen, 2013). These compounding and reinforcing effects can exacerbate pre-existing social inequities, and determine the pattern of displacement (e.g., short or long-term/permanent) among different populations. Additionally, decisions to migrate have been shown to be driven by social networks and connections and when members of a community have been displaced, others may make the decision to migrate (Manchin & Orazbayev, 2018).

In the absence of appropriate governance mechanisms and protocols for how and where to relocate displaced communities, negative feedback consequences for the Earth System are possible. Hosting communities may face strains on their natural resources and/or sinks to meet the additional needs of the displaced and conflicts may emerge between displaced and host communities. For example, Tafere (2018) identified environmental degradation resulting from the influx of displaced

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populations in East Africa, often in environmentally sensitive (e.g. protected forests) or already strained regions (e.g. arid or semi-arid areas).

2.4 Conflict

Despite growing concerns about conflict, the causal link between climate change and conflicts as well as their underlying dynamics remain debated (Buhaug, 2010; Buhaug et al., 2014; Solow, 2013, Selby et al., 2017). While statistical models inferred either significant coincidences of particular civil conflict events with concurrent climate extreme events or significant associations of warming and drought trends with civil conflict trends, many qualitative in-depth assessments of the particular civil conflict events and their underlying mechanisms dismiss such coincidences and associations (Buhaug, 2010; Burke et al., 2009; C. P. Kelley et al., 2015; Selby et al., 2017). Though not the only cause (Sakaguchi et al., 2017; Mach et al., 2019; Scartozzi, 2020; Ge et al., 2022), climate change undermines human livelihoods and security, because it increases the vulnerability of populations (e.g. to extreme events, food/water scarcity), grievances, and political tensions through an array of indirect – at times non-linear – pathways, thereby increasing human insecurity and the risk of violent conflict (Scheffran et al., 2012, van Baalen & Mobjörk, 2017; Koubi, 2019; von Uexkull & Buhaug, 2021; Ide et al., 2023). It is difficult to separate mutually enforcing vulnerabilities to both climate and conflict that trigger an escalating spiral of violence and amplify cascading crisis events beyond critical thresholds and connected through telecoupling (Franzke et al., 2022). Many conflicts can be described in terms of social tipping mechanisms, and tipping can be triggered by Earth system destabilisation (Guo et al., 2018, Aquino et al., 2019, Sun et al., 2022, Ge et al., 2022, Guo et al., 2023). Using a complex systems lens and connecting the human–environmental–climate security (HECS) nexus framework (Daoudy 2021, Daoudy et al., 2022) and the social feedback loop (SFL) framework (Kolmes, 2008) can help clarify conflict tipping mechanisms in coupled social-ecological systems. But there remain gaps in understanding latent mechanisms which introduce variable delay (e.g., slow social transformations), confounding factors, and non-linear bifurcations (e.g., some transformations are irreversible) and regional variability.

When conflicts escalate, exhibiting a tipping dynamic, they can in turn impact the Earth system, either directly as warfare itself is producing excessive GHG emissions and destroying vital ecosystems such as forests, as is for instance currently the case of Russia's war in Ukraine (de Klerk et al., 2022). But even beyond involvement in war activities, everyday military operations directly generate vast emissions of GHGs (Kester & Sovacool 2017, Crawford 2019). The feedback impact of conflicts on the Earth System can also occur indirectly through impeding humanity's ability to collaborate to find solutions to global challenges such as climate change. Within societies entangled in a conflict, resources are diverted to winning the conflict rather than to mitigate climate change, also affecting a country's environmental governance mechanisms.

2.5 Financial Destabilisation

The impacts of Earth system destabilisation on the financial sector are now receiving increasing attention, with studies suggesting that climate-related damages will impact the stability of the global banking system significantly (Lamperti et al., 2019). For instance, stocks of capital at risk due to climate-induced extreme weather events such as floods, would adversely affect insurance companies (Lamperti et al., 2019). Reinsurance companies are withdrawing increasingly from areas, exposed to high climate change risks, e.g., areas vulnerable to wildfires and floods (Frank, 2023). Earth system destabilisation is likely to result in stranded assets (Caldecott et al., 2021). Escalating climate change can also destroy the capital of firms, reduce their profitability, deteriorate their liquidity, reduce the productivity of their workforce, leading to a higher rate of default, harming the financial sector (Dafermos et al., 2018). One issue with the existing empirical evidence and models that try to estimate climate damage for the financial sector is however that they do not account for Earth System tipping points (Keen et al., 2022).

The inability to repay obligations generates non-performing loans (or bad debt) in the balance sheets of banks and other financial institutions, with possible systemic implications such as those experienced during the 2008 global financial crisis. It is predicted that climate change will increase the frequency of banking crises by 26% to 248% depending on the extent of climate change (Lamperti et al., 2019). If the banks' equity deterioration due to economic imbalances reaches a certain threshold, secondary systemic effects are triggered. Financial institutions exposed to troubled banks would suffer losses in the market value of their assets, potentially triggering contagion phenomena (Kiyotaki & Moore, 2002; Yan, Woodard & Sornette, 2010; Roukny et al., 2013; Chinazzi & Fagiolo, 2015). These contagion phenomena can result in a financial tipping point being reached, when contagion becomes self-perpetuating due to feedback loops in the system that amplify the initial shocks (Haldane & May, 2011; May et al., 2008, Gai & Kapadia, 2010). If Earth system tipping points are triggered, destroying assets and the economic productivity of whole regions, we can expect rapid non-linear tipping point effects in the coupled financial sector (Battiston et al., 2017). The financial and economic system would eventually settle into a new stable phase, although this phase may be characterized by recession, high unemployment, austerity, and other deteriorating economic conditions. The consequences of such a financial crisis are often a rapid increase in social instability (i.e., interaction with anomie), increase in radicalisation (i.e., interaction with radicalisation) as more people are forced to compete for basic needs, and conflict (i.e., interaction with conflict).

3 Cascading Negative Social Tipping Dynamics

The basis for many tipping point behaviours in social-ecological systems is a non-linear relationship between critical pairs of variables. Non-linearities create disproportionate relationships between cause and effect, potentially leading to change that is faster, more intense, or more extensive than expected (and hence, harder to reverse or control). Cascades are more likely when multiple variables within a given system exhibit non-linear relationships to each other. Crossing multiple negative tipping points in diverse systems increases the likelihood of (partial or localised) societal collapse. Below we give examples of cascades that have been identified in the literature.

Understanding the relationship between climate change, migration, and conflict has gained prominence in research as climate change is projected to increase both internal and external migration patterns dramatically in the coming years. The potential for tipping points in the Earth system poses additional uncertainty and risks that could alter and potentially exacerbate the dynamics between environmental conditions, food insecurity, migration, and conflict. Climate-induced migration is usually temporary (Black et al., 2011), but can be either short-term (seasonal and circular) or long-term (life cycle) (Brzoska & Fröhlich, 2016), and may be intra-rural, rural-urban, urban-rural, or international in nature. Therefore, defining a tipping point in a socioecological context is crucial. This is most frequently defined as 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 feedback mechanisms' (Winkelmann et al., 2022).

Cascades, as defined by Klose et al. (2021), are sequential occurrences of events in which an initial event triggers a series of subsequent events and are one important attribute of systemic risk (Sillmann et al., 2022). In the context of migration, this can manifest as a domino effect, where an environmental or socio-political event causes displacement (involuntary) or voluntary migration as people search for improved living conditions and better economic opportunities. This is well documented in the Lake Chad Basin case where climate change and unsustainable resource management affect the sustainability of natural resources, increasing vulnerability and leading to coping strategies such as migration (McLeman et al., 2021).

A possible tipping cascade can be identified between climate change, food insecurity, migration and conflicts. The last five years have seen an unprecedented increase in food insecurity, representing a problematic reversal of the progress done since the 1990s to reduce world hunger (FAO et al., 2022). This trend is largely attributable to intensifying conflicts, the effects of the COVID-19 pandemic, and more extreme weather events driven by climate change. Climate tipping points could dramatically impact food security through direct impacts on production (availability) and indirect impacts on access to food when displacement occurs. One of the most direct ways in which tipping points can affect food insecurity is through changes in rainfall distribution which would render agricultural livelihoods in rainfed regions unfeasible without irrigation (or other) technologies (Giannini et al., 2017; Benton et al., 2017). Food security can change seasonally. As such, food security does not exhibit traditional bifurcation in the sense of irreversibility. However, a permanent change towards a state of food insecurity would be catastrophic, representing a permanent food crisis. Krishnamurthy et al. (2022) offer a framework to identify "transitions" as prolonged periods of food insecurity (Figure 3), using the Integrated Food Security Phase Classification (IPC), the leading global metric for standardized food security assessment, which combines data on agricultural production, food prices, nutrition rates, weather patterns, and other variables to determine the general food security situation in a given location. With these metrics, a tipping point in a food system can be thought of as a shift between periods with minimal food insecurity (IPC 1 or 2) to periods of sustained food crisis (IPC 3 or higher). An example of a potential tipping point using the IPC categories was found in East Africa after the 2015/2016 El Niño episode. Usually, El Niño events yield extended autumn rains in East Africa, which is beneficial for livestock grazing (Korecha & Barnston, 2007). This was not the case for the 2015/2016 event, which saw anomalously low rainfall in both the summer and autumn. This trend, combined with insufficient drought preparedness, resulted in crop failures and livestock mortality–and consequently a depletion of livelihood assets, food stocks, and overall food security in northern and eastern regions of Ethiopia (Figure 3).

[FIGURE 3 HERE]

The links between food insecurity and migration are complex, severe food insecurity has been found to trap people locally, who wish to migrate, but are unable to (Sadiddin et al., 2019) but there is also evidence that migration can be driven by food insecurity (Smith & Wesselbaum, 2022). Migration flows are also impacted by climate change directly (i.e., the local environment becomes unsuitable for favourable habitation) and indirectly (i.e., by impacting relative wages through effects on farmers' crop yields). A climate disaster, for instance triggered by a climate tipping point being breached, may also lead to sudden displacement, whether temporary or permanent. Conflicts finally may arise because of competition over dwindling resources both in areas of destination, where newly arrived migrants may clash with host communities or face sustained marginalisation, and in areas of origin among 'trapped' populations unable to migrate outwards (Huber et al., 2023). To summarise, a cascading dynamic plays out when various tipping points become coupled, for instance, when the tipping in an Earth system, triggers the tipping in food insecurity and potentially simultaneously a tipping in displacement, with both contributing to a conflict tipping, which in turn may reinforce food insecurity.

4 Emerging research questions and intervention options

4.1 Methods and models and emerging data questions

Various methods and approaches have been suggested for the study of tipping processes in social and socio-ecological systems, which can be used to study negative social tipping points and the cascading interactions between them. In Table 1 we discuss the most prevalent methods and some new emerging approaches.

[TABLE 1 HERE]

Further emerging data questions include:

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- What are the most relevant and appropriate datasets for early warning of negative social tipping points? Social tipping points are more complex than physical tipping points due to the interacting relationships between climate parameters and social responses. Given this complexity, there is a need to identify relevant data sources and methods that can be used to detect and anticipate tipping points. Recent advances in machine learning and increasing digital social data all offer an unprecedented opportunity to understand early warning signals for social tipping points. Once datasets are identified, ensuring that these are accessible and usable for analysis is highly important. Moving forward, it will be important to consider sharing platforms to ensure access.
- What are the characteristics of datasets that can render them more (or less) useful for detecting social tipping points? A key, practical question for tipping point analysis is whether there are specific characteristics that make datasets more appropriate for detection of critical transitions. Early warning of tipping points ultimately depends on reliable, high-frequency data (Scheffer et al. 2009, Dakos et al. 2015). For example, in an analysis of data requirements for early warning of food security tipping points, Krishnamurthy et al. (2020) highlighted the importance of temporal resolution over spatial resolution to detect autocorrelation or flickering in coupled climate-food systems. However, research has shown that even limited datasets such as SMAP soil moisture can provide game-changing opportunities for detecting food security transitions (Krishnamurthy et al., 2022).
- Which early warning signals are more meaningful for different applications? Identifying the most useful metrics and statistics for early warnings of tipping points translates to actionable information, but it requires a clear understanding of underlying system functioning and mechanisms. For instance, in food security applications, autocorrelation is the key metric used to detect a transition in food security states, with the rolling average statistic indicating the direction of the transition (Krishnamurthy et al., 2022). Such insights can help leverage resources in a timely fashion to avert negative effects associated with social systems that exhibit tipping points.
- Moreover, probabilistic insights from research on collective social dynamics may complement insights from new early warning signals for social tipping. These approaches identify measurable qualities of social systems or networks, such as heterogeneity, connectivity and individual-based thresholds that make social tipping points more likely (Bentley et al., 2014). For maximum efficacy, these modelling efforts should derive from both qualitative and quantitative methods so as to benefit from both data and lived experience.

4.2 Intervention options and emerging policy questions

Given that negative social tipping points are under-researched, there is little knowledge on how they can be prevented or managed. As noted for instance by Milkoreit (2023), social tipping point governance has not really been developed. In Table 2 we nevertheless provide a preliminary overview of potential intervention options, linked to the discussed negative (social) tipping points and their main potential interactions. Future research needs to focus on identifying other potential intervention options and tying these together into a coherent tipping points governance framework. Ultimately, effective governance negative social tipping points will hinge upon the understanding of collective social dynamics and proactive resource-based interventions.

[TABLE 2 HERE]

Further emerging policy questions include:

- How do multiple climate extremes and other shock and stressors combine, especially as slow onset climate change processes occur to drive systemic changes and tipping points? Evidence provided here, suggests that severe climate events, such as droughts and hurricanes, can result in highly complex social change, including negative social tipping points. Additional research is required to understand if and how climate and social tipping points interact, and whether one tipping point can result in a plethora of other transitions.

- As critical transitions unfold, how does the risk landscape shift in response? Societies respond to environmental stress and resource scarcities. However, these responses may lead to new risks. Understanding how critical transitions affect the current (and future) risk landscape can provide essential information for decision-makers to prioritize investments in adaptation and mitigation.
- What are the processes required to integrate research into policy making? There is growing research on early warning signals for tipping points. However, once suitable datasets and early warning diagnostics are identified, what are the enabling processes and steps required to integrate actionable early warning systems into decision-making? New data analytics, dashboards and communications material may go a long way towards facilitating the transition to early warning systems of tipping points that can translate into action.

5 Conclusion

We mapped selected key potential negative social tipping points and their potential cascading interactions. We have also briefly discussed potential intervention options and provided examples of methods and models that need to be advanced in the future. We do not claim to have captured all possible social negative tipping points in the context of Earth system destabilisation, and we acknowledge that other social subsystems could experience negative tipping points as well, e.g. breakdown of (certain) global supply chains (Marcucci et al., 2022), or breakdown of the public health system (at least in certain areas) triggered for instance by a massive freak heat event or the breakout of a disease due to climate change (Skinner et al., 2023). Our goal is to highlight that if societies fail to stabilise the Earth system through decarbonisation, land use reallocation and other measures, societies will not merely stay in the business-as usual state. Through mechanisms of negative social tipping accompanying further Earth system destabilisation, they instead risk transitioning into a new social system state, which may be characterised by greater impoverishment, authoritarianism, hostility, discord, violence and alienation. Societies at greater risk of climate change impact are likely to experience such negative social tipping sooner, but this will inevitably have knock-on effects globally.

The acceleration of climate tipping points perpetuates a vicious cycle that weakens societies and their abilities to respond further, feeding further Earth system destabilisation, this vicious cycle is also fed by widening socioeconomic inequalities (Millward-Hopkins, 2022). As the consequences of climate change intensify, societal trust, cooperation, and altruism may erode due to increased competition for scarce resources, displacement of populations, and other climate-related challenges. Our knowledge on negative social tipping points is still very patchy and fragmented, with many estimations and models, likely to be underestimating the effects of breaching Earth system tipping points. This is particularly true for economic and financial sector models. Researchers (Keen et al., 2022) are advocating for developing future loss calculations in close collaboration with climate scientists to ensure adequate representation of climate catastrophes.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Earth System Dynamics.

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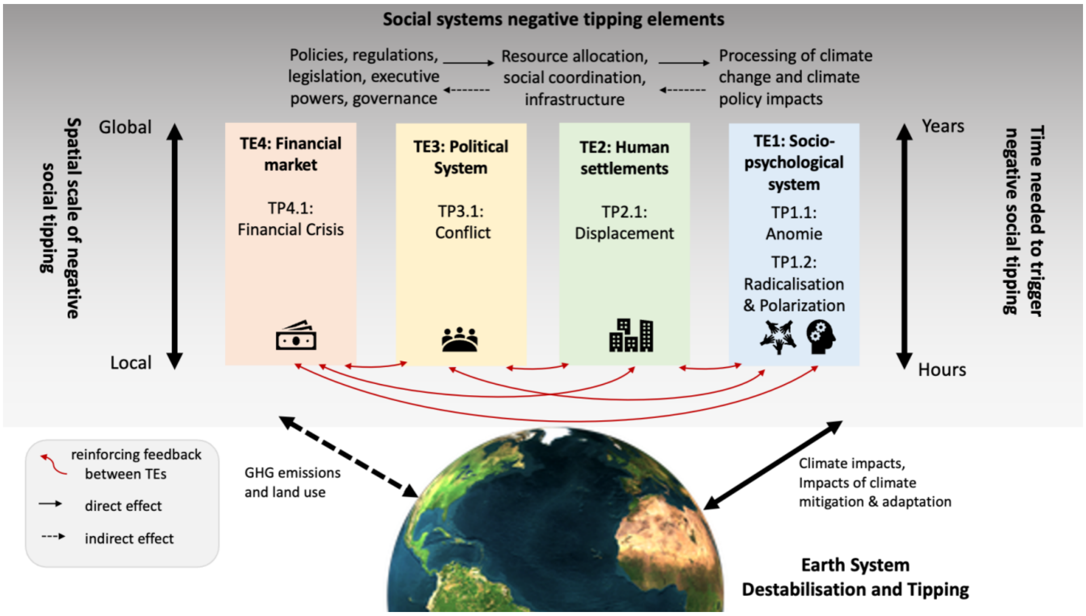
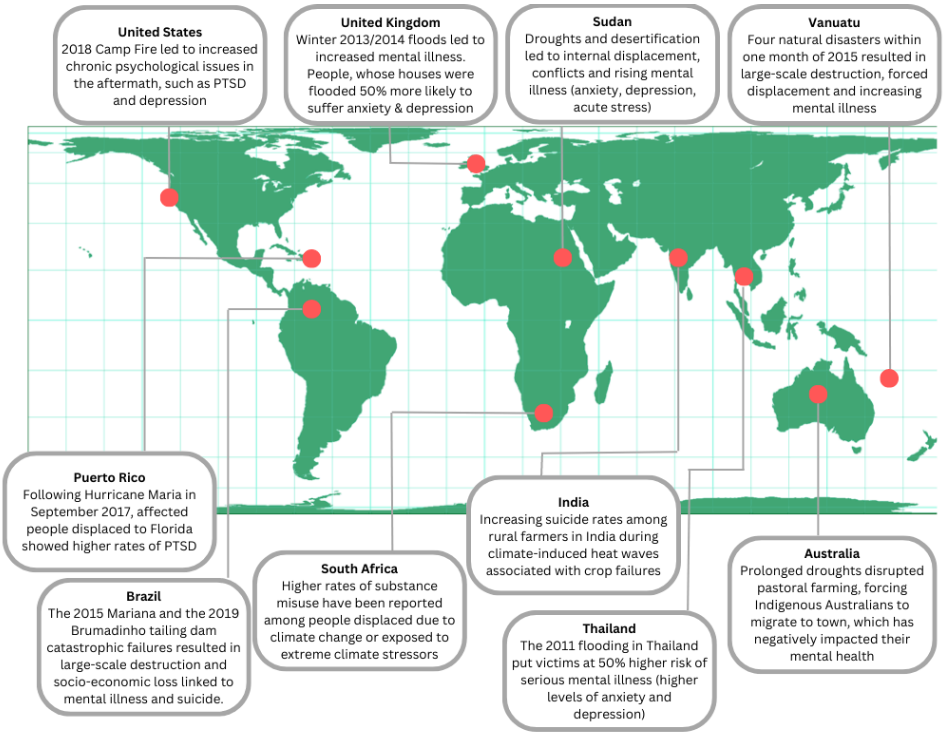


Figure 1: Tipping elements (TEs) and associated negative social tipping processes (TPs) with the potential to further destabilise the World–Earth system. The processes they represent unfold across levels of social structure on different time- and spatial scales. Tipping in all tipping elements can occur very rapidly (hours), triggered by a major shock event or unfold more slowly (years) over cascading pathways as the effects of Earth system tipping accumulate. Tipping can also occur only locally, affecting a specific community and spread across the globe. The identified interactions between the various negative tipping processes mean that they can potentially reinforce one another, making destabilisation more likely. Earth image source: https://pngimg.com/image/25350 (License: License: Attribution-NonCommercial 4.0 International (CC BY-NC 4.0))



United States
2018 Camp Fire led to increased chronic psychological issues in the aftermath, such as PTSD and depression

United Kingdom
Winter 2013/2014 floods led to increased mental illness. People, whose houses were flooded 50% more likely to suffer anxiety & depression

Sudan
Droughts and desertification led to internal displacement, conflicts and rising mental illness (anxiety, depression, acute stress)

Vanuatu
Four natural disasters within one month of 2015 resulted in large-scale destruction, forced displacement and increasing mental illness

Puerto Rico
Following Hurricane Maria in September 2017, affected people displaced to Florida showed higher rates of PTSD

India
Increasing suicide rates among rural farmers in India during climate-induced heat waves associated with crop failures

Australia
Prolonged droughts disrupted pastoral farming, forcing Indigenous Australians to migrate to town, which has negatively impacted their mental health

Brazil
The 2015 Mariana and the 2019 Brumadinho tailing dam catastrophic failures resulted in large-scale destruction and socio-economic loss linked to mental illness and suicide.

South Africa
Higher rates of substance misuse have been reported among people displaced due to climate change or exposed to extreme climate stressors

Thailand
The 2011 flooding in Thailand put victims at 50% higher risk of serious mental illness (higher levels of anxiety and depression)

Figure 2: Examples of the impact of extreme weather events on mental health across the world, based on Carleton (2017); Clayton et al. (2017); Jermacane et al. (2018); Atwoli, Muhia & Merali (2022); Hamideh, Sen & Fischer (2022); Lawrence et al. (2021), and Ferreira et al. (2023).

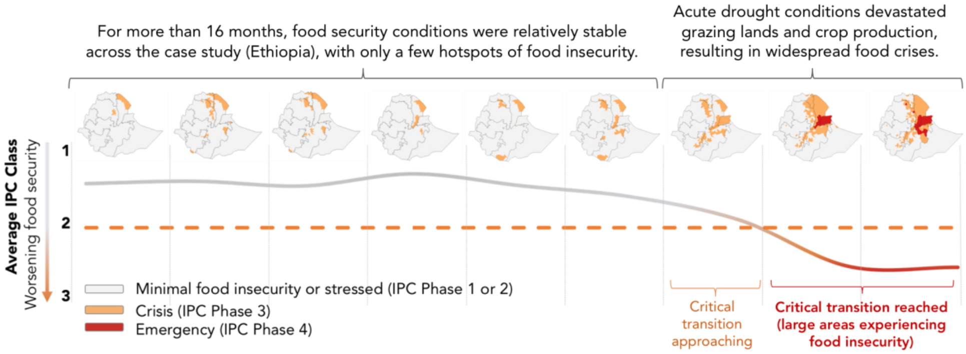


Figure 3. Example of a "tipping point" in the context of food security, showing the transition from stable food security conditions to a food crisis resulting from drought in Ethiopia (Source: Krishnamurthy et al., 2020)

Table 1. Models and Methodological Approaches for Studying Negative Social Tipping Points and Cascades

Model / Approach	Rationale	Modelled phenomena	Examples	Further Questions
(Complex) Contagion Processes on (Social) Networks	In a simple contagion direct exposure to a viral entity (beliefs, behaviours, emotions, price signals) is sufficient for a node to get "infected". In a complex contagion a node gets "infected" if a certain number (can be heterogeneous) of its neighbour nodes are infected (Guilbeault, Becker & Centola, 2018; Wiedermann et al., 2020; Andreoni et al., 2021). Models of contagion on networks can be used to study radicalisation, anomie, and financial tipping.	In a contagion a viral entity spreads initially gradually until a critical threshold (critical number of "infected" nodes) is reached at which stage the social system tips through saddle-node bifurcations and hysteresis. Hysteresis ensures that the contagion spreads further and leads to the phase transition, even if the original seeders of the viral entity are removed from the network, i.e., the contagion processes become self-reinforcing (Dodds & Watts, 2004; Wiedermann et al., 2020; Xie et al., 2021). Network structure (e.g. clustering) can facilitate or prevent various contagion processes (Guilbeault & Centola, 2021).	Research shows that beliefs (incl. misinformation), mental states, behaviours and practices (e.g. technology adoption) can spread through complex contagion across social networks (Karsai et al., 2014; Törnberg, 2018; Fink et al., 2021; Xie et al., 2021; Alexander et al., 2022). Research on financial contagion also shows that volatility can spread across a network of financial institutions (Summer, 2013; Wunderling et al., 2021).	There are gaps in our understanding of the mechanisms underlying complex contagion in the real world, where at any given time, multiple, conflicting diffusion processes are taking place (Min & Miguel, 2018; Vasconcelos et al., 2019; Yletyinen et al., 2021).
Logistic Maps Models	The logistic map is a mathematical function that models the population change of an ecosystem over time and it is a useful tool for policy and climate analysis as it represents a wide range of regular and chaotic features (Feigenbaum, 1980; Bruun, Allen & Smyth, 2017). Logistic Maps can be used to study anomie social tipping and cascading dynamics for instance in financial and political systems.	The logistic map provides the capability to investigate non-abrupt and/or reversible tipping point changes that are features of the system. It represents the socio-economic system through the population level, at time t, as X_t, and its future population state at time t+1 is specified by the non-linear relationship X_(t+1) = r X_t (1-X_t). It enables us to identify and explore tipping point transitions and complexity cascades properties across a set of different system types.	Logistic maps have been used to model financial and economic cycles and crises (Ausloos & Dirickx, 2006, Guégan, 2009). Logistic maps have also been employed to study conflicts (Guastello, 2008)	The model could be useful to study phenomena such as anomie, where the ecological and social system are closely coupled and the tipping in the ecological system would have direct repercussions for the social system with one possible outcome being disintegration of the social system, i.e. chaotic, random and irregular behaviour of agents in the social system.
Causal Loop Diagrams (CLD) and Causal Inference	Causal loop diagrams (CLD) are a structural approach for systemic risk assessment on different scales and to identify whether a society is at risk of reaching a negative social tipping point (Groundstroem & Juhola, 2021; Sillmann et al., 2022). Causal inference is the attempt to empirically test causal assumptions. CLDs and causal inference can be used to study displacement, conflicts, and cascading dynamics.	CLDs map out the structure of a system and its networks and reveal causalities and feedbacks within the system (Haraldson, 2004; Sanches-Pereira & Gómez, 2015). Variables are connected with arrows that indicate positive or negative causal links between them. Links between variables may have temporal delays (Sanches-Pereira & Gómez, 2015). Feedback effects arise when variables affect each other in a cascading manner, ultimately leading back to a previous variable, creating a feedback loop. This loop can be either reinforcing (R), leading to unbounded growth or decline, or balancing (B), if some variables create counteracting changes, resulting in equilibrium.	CLDs have been used to model socio-ecological system dynamics, for instance the coupling of climate change, food insecurity and societal collapse (Richards, Lupton & Allwood, 2021). Causal inference has been used to model for instance climate induced conflict as an excitation causal process (Sun et al., 2022). Machine learning methods have also been used for causal inference, i.e. to self-discover causal trees between Earth system and social systems (Ge et al., 2022).	Improving causal understanding of how changes in the Earth system affect social systems is challenging when many of the latent mechanisms and pathways lack data, and when different regions experience diverse mechanisms. End-to-end causal inference has limited success (Guo et al., 2023).
Multi-Stable Differential Equation Models	Dynamic approach, aligned to the dynamical systems theory (Hirsch, Smale & Devaney, 2012), analyse time	The specific functional form of the models can vary depending on the studied phenomenon. A tipping model can be for	Multi-Stable Differential Equation Models have been also used for assessing the risks of emerging	The models rely on rich and dense multiple time-series data. They are also constrained in terms of

	series data to identify possible phase transitions from stability to instability until a new equilibrium is found. Differential equation models can have multiple equilibrium points, where the rate of change of a variable (e.g., degree of cooperation) does not change further. These models can be used to study negative social tipping phenomena, where sufficient time-series data is available, e.g. conflicts and financial systems tipping.	instance a 3rd-order polynomial in the form of a bi-stable ordinary differential equation (ODE): $dx/dt = x(x-C)(x-K)$. Here, we can see that the rate of change ($dx/dt = 0$) has three equilibrium points: $x=0$, $x=C$, $x=K$. Two of the three equilibriums are stable, e.g. a small perturbation will cause the system to return to the closest point 0 (conflict) or $K>C$ (cooperation). One of the three is unstable, e.g., a small perturbation will cause the system to deviate away completely (this is the tipping criticality point C).	tipping cascades in interconnected climate tipping elements (Krönke et al., 2020; Wunderling et al., 2023) and financial systems (Wunderling et al., 2021) using Monte Carlo approaches to propagate parametric and structural uncertainties. They have also been used to study conflict dynamics (Aquino et al., 2019).	complexity representation. This results partly from their aggregate nature, as they are mainly concerned with macro-level dynamics, as such they might be less suitable where micro-level interactions are of interest.
Agent-Based Modelling (ABM)	Agent-Based Modelling (ABM) represents the rule-based behaviour and interaction of individual agents which ranges from simple homogenous to complex heterogeneous agents characterised by diverse response functions regarding their motivation and reasoning, capability to act and adaptive learning, perception and anticipation of changing environmental situations (BenDor & Scheffran, 2019). ABMs can be used to study conflicts and cascading dynamics.	Multiple agents show collective behaviour via opinion dynamics, coalition formation, network building, inducing social feedback, structural shifts, social norms, and transformative policies, including the transition between conflict and cooperation (Juhola et al., 2022). ABM captures macro-scale phenomena from micro-scale interactions among many heterogeneous adaptive and learning agents with bounded-rationality (Filatova et al., 2013; Weber, Constantino & Schlüter, 2023).	ABMs are applied to study agents' adaptation behaviour and the possible limits to adaptation (Juhola et al., 2022). ABM are well suited to model game-theoretical approaches to predict agent-induced tipping points when collaboration for instance breaks down (Grimm & Schneider, 2011). They can simulate self-reinforcing chain reactions and cascading effects in dynamic social networks (BenDor & Scheffran, 2019).	Where ABMs lack empirical foundation (i.e., no data), it is difficult to verify the predictions they are making. They can be useful to generate hypotheses and explore theoretical mechanisms, which should be tested empirically.
Machine Learning (ML)	Machine Learning (ML) approaches have been already mentioned in the context of previous sections (causal inference). But ML methods can also be used to explicitly detect tipping points (Bury et al., 2021). ML approaches can be used to study negative social tipping phenomena, where sufficient time-series data is available, e.g. conflict, financial systems tipping etc.	ML models have been used for instance to model bifurcations, i.e. the divergence of an outcome trajectory. These are often mechanism-informed ML models. Hawkes excitation model has been used for instance to model the coupling between successive improvised explosive device (IED) attacks and security retaliation (Tench et al., 2016). Point process modelling has been used to identify complex underlying processes in conflicts, such as diffusion, relocation, heterogeneous escalation, and volatility (Zammit-Mangion et al., 2012).	ML approaches can be useful to forecast tipping in conflicts for instance (Guo et al. 2018). With increasing availability of rich digital data, negative social tipping processes (e.g. radicalisation or social disintegration) could be detected using for instance Deep Learning models in combination with social network analyses (Gaikwad et al., 2022). ML-based tools are also emerging to predict tipping in financial systems (Samitas et al., 2020)	Pure data driven prediction models (e.g., using Gaussian Processes, Deep Recurrent Neural Networks), typically lack the ability to model irreversible transformations, such as tipping and understand causal relation strength. But if sufficient data is available and if the ML models are informed by theory and deep understanding of the underlying mechanisms (Guo et al., 2018) they can be a useful method.

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Table 2 Negative (social) tipping points and options for prevention and impact management

Negative (Social) Tipping Points	Prevention Options	Impact Management Options
Earth System Tipping Impacts (e.g. food insecurity)	Early warning systems to detect escalating food insecurity and anticipatory action mechanisms, incl. investment in irrigation, crop diversification and investment in long-term adaptation options to improve climate-smart agriculture (Krishnamurthy et al., 2020)	Risk finance (e.g., weather index insurance) (Benso et al., 2023) and emergency response (e.g., food assistance), managed relocation from areas that become uninhabitable/uncultivable (Ferris & Weerasinghe, 2020).
Anomie	Strengthening resilience of individuals and communities (Ogunbode et al., 2022). Strengthening social cohesion (Orazani, Reynolds & Osborne, 2023). Ensuring authorities can respond to ecological hazard effectively through capacity building and resilient infrastructure (Miller, 2016; Brown, 2020)	Mental health support to individuals and communities affected by extreme weather events and displacement (Wood & Kallestrup, 2021). Working with affected communities to re-build and integrate displaced communities in host communities (Hawkins & Maurer, 2011)
Radicalisation & Polarization	Preventing the spread of misinformation/ disinformation (Aïmeur, Amri & Brassard, 2023). Psychological inoculation against misinformation/disinformation (Van der Linden et al., 2017). Monitoring radicalisation. Radicalisation prevention programmes. Public engagement in democratic, deliberative decision making (Devaney et al., 2020).	Deradicalization and dialogue building programmes (Kimmel, 2018; Hangartner et al., 2021). Containing the influence of radical groups (Flache et al., 2017). Early warning systems for detecting the potential for violence (Guo et al., 2018).
Displacement	Early warning systems and anticipatory action mechanisms, e.g. managed relocation. Investing in resilience of displaced communities, through stability, education, and employment opportunities (Ferris & Weerasinghe, 2020).	Host community and refugee support (e.g., humanitarian support, food aid, housing, mental health support) (Pearce, Murphy & Chrétien, 2017). Financial compensation for host communities. Legal frameworks and policies to support mixed movements (McAdam, 2012)
Conflict	Conflict early warning systems (CEWS) (Guo et al., 2018). Conflict prevention processes, through conflict management, democratic procedures. Agreements on scarce resource management and distribution. Climate change adaptation support. Resilience building of societies at risk of violent conflict (Abrahams, 2020)	Conflict resolution process (Ngaruiya & Scheffran, 2016). Humanitarian support to citizens trapped in conflicts. Managed relocation from active fighting zones.
Financial Destabilisation	Early and stable transition away from fossil fuel assets (i.e. divestment). Implementation of a green corporate quantitative easing programme to reduce climate-induced financial instability and restrict global warming (Lamperti et al., 2019)	Macroprudential regulation in climate risk management. A counter-cyclical capital buffer (as proposed in the Basel III framework) could help address climate physical risks, even though it may be insufficient when damages surge (Lamperti et al., 2019)