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# Tipping cascades between conflict and cooperation in climate change

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**Abstract**: Following empirical research on the dynamics of conflict and cooperation under climate change, we discuss complex transitions and interactions, connected to models of tipping points, compounding and cascading risks. In the context of multiple crisis, pathways in the climate-conflict nexus are analysed, with conflict-relevant conditions, risk indicators and societal responses to compounding effects of conflict risk and climate vulnerability. System and agent models of conflict and cooperation are considered to analyze dynamic trajectories, equilibria, stability, chaos and empirical simulations as well as adaptive decision rules in multi-agent interaction and related tipping, cascading, networking and transformation processes. A bi-stable tipping model is applied to study transitions between conflict and cooperation, depending on internal and external factors as well as multi-layered networks of agents, showing how negative forces can reduce resilience and induce collapse to violent conflict. The case study of Lake Chad is used to demonstrate climate change as a risk multiplier in the model. For poor governance, community behavior is facing low barriers to climate stress which can tilt towards conflict, while resilience can build barriers against it. Narratives confirm that forced migration and militant forces lower the barrier and the chance for cooperation. Adaptive and anticipative governance based on integrative research and agency can prevent and contain climate-induced tipping to violent conflict and induce positive tipping towards cooperative solutions and synergies, e.g. through civil conflict transformation, environmental peacebuilding and forward-looking policies for Earth system stability.

**Keywords:** Tipping cascades, climate-conflict nexus, conflict and cooperation, conflict models, complex networks, agency.

## 1 Complexity challenges in security, conflict, and multiple crises

### 1.1 Introduction

In the Post-Cold War era, the international security landscape has become increasingly complex, expressed in the "complexity turn" of international relations (Urry, 2005; Scheffran, 2008). In the new world (dis)order and multiple crises, also named *polycrisis*, cascading chains of events are emerging, including complex social interactions and self-reinforcing collective dynamics such as stock market crashes, migration, pandemics and violent conflict that increasingly challenge international security and stability (Scheffran, 2015; Homer-Dixon et al., 2022). A particular form of social instability contributing to crises is conflict, based in incompatible values, priorities, and actions of agents who undermine each other's values and provoke hostile responses, leading to escalating interactions in situations where conflicts are not resolved.

While there is substantial understanding regarding the dynamics of conflict and cooperation based on quantitative and qualitative empirical methods, modeling and systems dynamics approaches have played only a marginal role in the analysis of transitions between conflict and cooperation and related switching of behavior, as well as in the analysis of micro-macro transformations in international security and multi-scale self-organization which may accelerate beyond tipping points. In a world at the edge of chaos, in which everything is interconnected, changes in one part of the world can have significant impacts elsewhere and propagate through systemic networks like a domino effect or chain reaction (Kavalski, 2015) of multiplying consequences. A better scientific understanding of the underlying complex interactions is a prerequisite to stabilize the Earth

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system and to enable forward-looking adaptation-oriented policies that prevent violent conflict and enable cooperative stabilization of the Earth system. With this paper, we aim to improve the understanding of current issues of conflict and cooperation, in particular in climate and environmental conflict, by connecting to the research on tipping points, compounding and cascading risks. Research gaps will be addressed by questions on critical thresholds for tipping cascades, conditions for stability and instability across the conflict-cooperation divide, and the role of adaptive and anticipative responses. Following the introduction of key terms related to tipping points in the next subsection and discussion of the climate-conflict nexus in Sect. 2, a focused review of relevant tipping models in conflict and cooperation is given in Sect. 3. The conflict-cooperation transition is presented in the bi-stable tipping model of Sect. 4, followed by the case of the Lake Chad hot spot in Sect. 5, and discussion of governance challenges for conflict transformation and environmental peacebuilding in Sect. 6.

### 1.2 Tipping points, compound risks and cascades in social systems

The growing research on compound events, tipping elements, chain reactions and risk cascades provides insights on complex transitions between qualitatively different states in natural and social systems, which accordingly is adequate to learn about interactions and transitions between conflict and cooperation. The following gives a short introduction to key terms.

*1. Compound events*: Environmental risks can be amplified by the combination of multiple stressors and hazards, the co-occurrence of which contributes to societal and/or ecological risks (Zscheischler et al., 2018). Examples include the interaction of different weather phenomena and climate change impacts, such as extreme precipitation and wind damaging infrastructures, storm surges and precipitation resulting in coastal flooding, or drought and heat leading to tree mortality and vegetation fires. The latter can cause air pollution, affect crops, and harm human health, as in the summer of 2010 in Russia (Reichstein et al. 2021). In hurricanes in the United States such as Katrina in 2005, Sandy in 2012, and Harvey in 2017, the coincidence of heavy rainfall and storm surge had a devastating effect, causing massive damage and loss of life in urban centers. Certain compound effects are represented in the nexus approach, such as the water-food-energy nexus or climate-conflict-migration nexus.

*2. Tipping points and thresholds:* At the critical threshold to instability, even small changes can cause a system to tip, symbolized by the butterfly effect known from chaos theory. Around a bifurcation, small causes have large effects, associated with dramatic system changes that can propagate (Scheffer 2009). Beyond tipping points, affected systems fall into a qualitatively different state from which often there is no easy return. A spectacular political example was the fall of the Berlin Wall in 1989, which served as a tipping point for the domino-like collapse of the Soviet world system in a matter of weeks, the end of the Cold War, and German unification (Jathe and Scheffran 1995). For tipping points in political contexts, it has been suggested "that events and phenomena are contagious, that little causes can have big effects, and that changes can happen in a non-linear way but dramatically at a moment when the system switches" (Urry, 2002:8). According to Milkoreit et al. (2018: 9), a tipping point is a "point or threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible." Thus, tipping points are characterised by multiple stable states, non-linear change, driving feedbacks and limited reversibility. Most prominent are tipping elements in the climate system which include self-reinforcing melting of the Greenland and West Antarctic ice sheets, release of frozen greenhouse gases such as methane, weakening of the North Atlantic Current, or changes in the Asian monsoon (Lenton et al. 2008). Above a critical temperature threshold, amplification effects and chains of events could lead to fundamental Earth system changes reaching planetary boundaries (Steffen et al. 2018). When certain thresholds and tipping points are violated, they would trigger abrupt and irreversible tipping cascades that endanger global and regional stability, including social tipping (Otto et al., 2020; Franzke et al., 2022). Whether these are "negative" or "positive" tipping points depends on an assessment of their advantages and disadvantages.

*3. Risk cascades and chain reactions:* Beyond critical thresholds and tipping points, complex dynamics are possible, such as phase transitions, risk cascades, and chain reactions (AghaKouchak et al. 2018). An example is the exponential chain reaction of nuclear fission, which is uncontrolled in the atomic bomb and held at the threshold of criticality in the nuclear reactor by

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control rods to extract energy. A reactor accident can set in motion global cascades of consequences, as demonstrated by the nuclear disasters at Chernobyl in 1986 and Fukushima in 2011. Sometimes the switching results from triggering events, such as disasters, mass migrations or social movements with self-enforcing cascading sequences, e.g., when an action taken by one actor provokes more intense actions by other actors. Exponential cascades are also demonstrated by the Corona pandemic, in which all humans are part of a virus chain reaction. Climate change can also connect to cascades in social networks, in protest movements, elections, stock market crashes, revolutions, mass exodus, or violent conflicts (Kominek & Scheffran 2012). Tipping cascades can affect conflict through various pathways – e.g., risks to livelihoods, settlements, wellbeing, and cultural values leading to social changes, such as migration, human displacement, geopolitical tensions, and conflicts of different types. Cascading effects and risks beyond tipping points are difficult to contain or control and can extend beyond regions.

## 2. Conflict and cooperation in climate and environmental change

### 2.1 Conflict and cooperation as social interaction

Conflict and cooperation are important forms of social interaction. Conflict generally refers to social or political incompatibility of interests, values or actions between social actors who fail to reduce their differences and tensions to tolerable levels. These differences drive continued actions that escalate the conflict, including protest, resistance and violent acts causing mutual losses. Cooperation is the opposite interaction when the interests, values or actions of social actors are not only compatible but even beneficial, leading to mutual gains. Both conflict and cooperation are affected by human motivations and values (e.g., life, health, income, assets) as well as by capabilities and opportunities (e.g., money, resources, vehicles, equipment, technology). Both have direct and indirect impacts on human actions and responses that can drive and inhibit conflictive and cooperative actions, destabilizing interaction to a downward spiral of violence and a vicious circle of conflict escalation (Buhaug and von Uexkull, 2021) or be stabilized to a virtuous circle of solutions by governance mechanisms and institutional policies, separated by tipping points when interaction is qualitatively changing. Near thresholds of instability, a seemingly minor change can trigger rapid transitions between conflict and cooperation, escalation and de-escalation, war and peace, if no mediating and stabilizing measures are taken. Compound events, tipping elements and risk cascades can combine in "tipping cascades" triggering the transition processes between conflict and cooperation. Climate and environmental change can be among such events.

### 2.2 The environment-conflict nexus

Environmental change is potentially associated with a wide range of conflictive issues. The concept of security has been expanded to include ecological dimensions and the availability of natural resources. Environmental conflicts concern the use and degradation of exhaustible as well as renewable resources, regenerated in metabolic cycles, depending on the functioning and stability of ecosystems, which in turn are affected by conflicts. A lacking balance between human demands and available resources, together with an insufficient use and inequitable distribution of resource benefits and risks, contains a significant conflict potential. Conflicts in changing environmental conditions can arise from competitions, grievances, or greed in relation to scarcity and/or abundance of resources (Okpara et al., 2016), including situations of differing interests, values, incentives, and priorities amongst resource users.

Environmental change and violent conflict together can weaken social relations and social capital, e.g., when weather extremes disrupt infrastructures and stability of society, or violent conflict constrains the capacity of people and countries to adapt to climate change, which in turn makes recovery and peacebuilding more difficult (Juhola et al. 2022, Krampe, 2019). This can weaken the resilience of communities and institutions in places like Iraq and Somalia, hindering their ability to maintain peace. Conversely, conflict-related effects such as displacement or disruption of livelihood practices impede the capacity of

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communities and institutions to adapt to climate change in places like Afghanistan or Mali. Having lost savings and assets in conflict, impoverished communities in low-income countries are highly vulnerable to future risks and have few resources to respond: "Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (high confidence)." (IPCC, 2022). The double exposure to environmental and conflict risk is associated with compound effects where "environmental change can make societies more vulnerable to violence which in turn can make societies more vulnerable to environmental change, leading to a trap from which escape is difficult" (Scheffran et al., 2014: 375). It is difficult to separate mutually enforcing vulnerabilities to climate and conflict that escalate a spiral of violence and amplify cascading crisis events beyond critical thresholds and connected through tele-coupling (Franzke et al., 2022).

In changing environmental conditions cooperation can also emerge as a response – e.g., when governments and society collaborate and build alliances around environmental challenges, or initiate agreements and policy frameworks, leading to shared goals, fostering trust building and social cohesion (Lejano and Ingram, 2009; Huitema and Meijerink, 2018). Mutual adaptations of actions or institutional control mechanisms can stabilize the interaction and contain conflict. Understanding the interplay of conflict and cooperation (how they emerge, co-exist and shape social systems during a cascade of tipping points) is critical for defining pathways towards transformative change for peace and human/planetary security.

### 2.3 Climate change as a risk multiplier

Climate change is a conflictive issue, from disputes over scientific predictions, impacts und uncertainties of climate change to violent conflicts fuelled by the security risks of climate change. Studies on climate-conflict linkages discuss the effects of various climate phenomena (e.g., change of temperature and precipitation, resource availability, weather extremes, sea-level change) on different phases of conflict (onset, initiation, escalation, prolongation, termination, prevention). Measures to prevent and address climate risks can also become issues of conflict, in particular tensions over mitigation and adaptation, disaster management and damage limitation, climate geoengineering or the fair distribution of costs, risks, and benefits of climate change (Scheffran et al. 2012b). Conflict parties can be nations, individuals, parties, companies, trade unions, activist groups and generations, among others.

Understanding of the relationship between climate change and security risks has advanced significantly in recent years (Uexkull and Buhaug, 2021). While there were differing interpretations in past IPCC reports, research generally agrees that climate change not only exacerbates the causes and effects of conflict, but also affects the ability of communities and institutions to move towards cooperation and establish and maintain peace in specific contexts (Gleditsch and Nordås, 2014). The latest IPCC summary reaffirms with high confidence: "Climatic and non-climatic risks will increasingly interact, creating compound and cascading risks that are more complex and difficult to manage" (IPCC, 2023). Although certain regions have been neglected in research (Adams et al., 2018), there is now a substantial body of qualitative and quantitative studies from various disciplines that provide new insights into the link between climate change and security (De Juan, 2015; Brzoska & Fröhlich, 2016; Buhaug, 2015; Abrahams Carr, 2017; Scheffran, 2020a; Rodriguez et al., 2019). While climate change is not the sole cause (Mach et al., 2019; Sakaguchi et al., 2017; Scartozzi 2020; Ge et al. 2022), it undermines human livelihoods and security by increasing vulnerabilities, grievances, and political tensions through indirect and sometimes non-linear pathways, resulting in human insecurity and violent conflict risks (van Baalen & Mobjörk, 2017; Koubi, 2019; Uexkull & Buhaug, 2021).

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The context, timing, and spatial distribution of climate change impacts are crucial factors that need to be considered in assessing outcomes of conflict and cooperation (van Baalen and Mobjörk, 2017). Research has identified five risk dynamics that illustrate the spatial and temporal complexity of climate-related security risks and conflicts (SIPRI 2022). These include:

1. Compound risks, in which the simultaneous interaction of two or more risk factors results in a greater risk complex, as the factors mutually reinforce each other.
2. Cascading risks, in which an event creates a risk that leads to subsequent, sequential risks, generating an increasingly escalating risk potential like a snowball effect.
3. Emergent risks, in which two or more temporally and spatially independent factors create a new risk that would not have existed without the previous two.
4. Systemic risks, in which multiple risk factors interact in such a way that they cumulatively threaten a societal and/or ecosystem in parts or as a whole.
5. Existential risks, whose impacts are so severe that they threaten the existence of a country or culture, for example.

The relationship between cooperation, climate change and security risks therefore varies depending on context, is often indirect and not linear. Multicausality of conflict and feedback from conflict to climate further complicates the picture. For instance, 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, which is the case for Russia's war in Ukraine (de Klerk et al., 2022), hence further contributing to global warming. To make sense of the complexity of climate-related impacts on societies requires reducing the system to its core elements. Building on existing research on the relationship between climate change and conflict, Figure 1 describes the relationship and sets "climate change", "people's vulnerability" and "insecurity" as the three core variables to look at in each context (SIPRI, 2022). While there are several potential mechanisms that explain the relationship of climate change and conflict, they can be mostly summarized in four interrelated pathways that explain when climate-related vulnerability translates into physical violence. These pathways are: (1) livelihood deterioration, (2) migration and mobility, (3) existence of tactical opportunities for militant and armed actors, and (4) elite exploitation and political and economic grievances (Mobjörk et al., 2020).

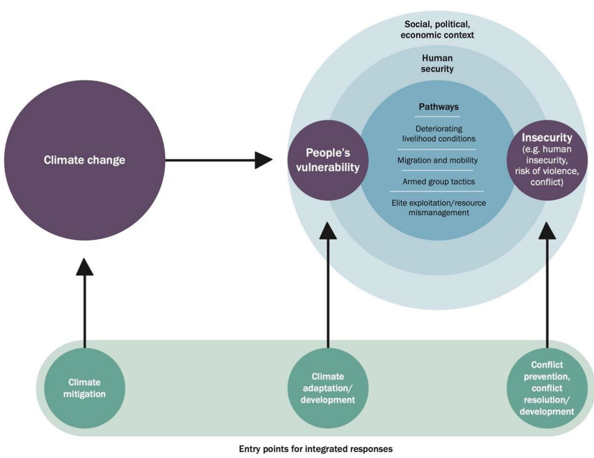


**Figure 1: Pathways and entry points of climate-security interaction (source: SIPRI, 2022: 63)**

1. Climate change undermines the livelihoods of societies, increasing the risk of conflicts. For example, changing weather patterns significantly impact agriculture and livestock farming, putting pressure on societies or specific populations whose income depends primarily on agriculture. This in turn leads to tensions, particularly at the local level, which can result in

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violent conflicts between different groups. In Somalia, for instance, the reduced resilience of the impoverished population affected by prolonged conflicts forces people to engage in informal activities such as illegal logging for charcoal production to secure their survival. The loss of livelihoods, which are often an integral part of personal identity, also leads people to join extremist groups not due to ideological conviction, but rather due to the personal need for belonging. Section 5 discusses the Lake Chad region, where young people who were formerly engaged in farming, pastoralism and fishing left these livelihood activities when drought and lake drying intensified, and many have now become either radicalized or ensnared into crime.

2. Climate impacts result in migration and changing mobility patterns, which in turn can lead to conflicts between incoming groups and the residents of destination regions. On the one hand, deteriorating living conditions drive more people to cities where there may be limited economic opportunities, leading to an increase in informal and illegal activities. On the other hand, floods or droughts also push population groups to rural areas where other groups already live, further straining local resources and causing tensions. The climate-induced changes in mobility patterns also do not occur smoothly. For example, in West Africa, nomadic populations are increasingly pushed into new regions bordering their traditional routes due to seasonal shifts and delayed rainy seasons. In these areas, many of their herds graze on land cultivated by sedentary farmers, disrupting traditional mechanisms that have regulated the coexistence of these groups in the past. If such disruptions occur in a context of unstable power relations or armed conflicts, these situations can quickly escalate.

3. Climate change influences the behavior of armed actors and directly affects conflict dynamics. This includes not only the military readiness of state and non-state actors, but also changing power dynamics. For example, insurgent groups in Mali and Somalia may find it easier to move in flooded areas compared to conventional forces, making the latter more vulnerable. Additionally, extremist groups can exploit societal grievances over the state's handling of climate change impacts to further their agenda, such as recruiting members or mobilizing support.

4. Climate-related security risks also affect governance structures and can exacerbate existing governance challenges. Climate impacts can strain government capacity and resources, leading to weakened governance institutions and ineffective policies. This can result in social unrest, loss of trust in institutions, and erosion of state legitimacy. In addition, climate change can create new power dynamics, with some actors gaining or losing influence because of changing resource availability or shifts in geopolitical interests.

These pathways suggest that climate-conflict relations (including cooperation linked to environmental change) can be understood through a variety of perspectives – political economy, environmental security, behavioural and human psychology, governance, and institutions, and social-ecological. Different pathways and perspectives are essential in understanding the transition between conflict and cooperation, which can shape (and be shaped by) human responses, climate policy(ies) and complex negotiations across multiple scales.

Conflict in climate policy can be linked to differing national interests, priorities, and values (Victor, 2011). Engagements to mobilize, allocate and distribute climate finance can lead to conflict under certain conditions; also distribution of responsibilities and burdens on net zero transitions can lead to conflict. For example, countries have divergent views on the level of climate mitigation actions required, as well as the allocation of costs, and the sharing of benefits - disagreements over mitigation targets, financing mechanisms, and technology transfer can lead to conflicts in international climate negotiations since countries have different levels of capacity, vulnerabilities, and historical responsibilities. Within countries, conflict can arise between different economic sectors, e.g., between fossil fuel-intensive industries and renewable energy proponents, or between environmental advocates and those pursuing "environmentally unsustainable" economic gains. In conflict zones, the

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presence of conflict economies (that thrive on the extraction of mineral/environmental resources) can hinder the adoption of climate policies, leading to policy gridlocks or delays in decision-making.

Considering the global nature of climate change, cooperation among nations is essential to drive effective climate policies. International climate agreements, such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement, are examples of cooperative climate policy efforts at a global level (Bodansky, 2016). Agreements such as these provide a framework for countries to work together to set beneficial adaptation/mitigation and technology transfer goals, and build solidarity and cooperation (e.g., to support the most climate vulnerable people and countries). Cooperation also happens at regional, national, and local levels, where stakeholders collaborate to develop and implement climate policies (Adger and Jordan, 2009). This may involve partnerships among governments, businesses, and civil society organizations to foster innovation, promote renewable energy update or implement climate adaptation measures (Pattberg and Stripple, 2008). Cooperative actions such as knowledge-sharing, capacity-building, and collaborative governance can help to create synergy and facilitate effective climate policy implementation.

**2.4 Climate conflict, social tipping, and agency**

While there is substantial understanding regarding the dynamics of conflict and cooperation in the context of climate change, largely neglected in current conflict research remains the concept of tipping points – critical thresholds that, when surpassed, can trigger significant changes in natural and social systems. While research has largely focused on natural tipping point, with severe and often unknown consequences for security, conflict, and cooperation, much less attention has been paid to social tipping points in the context of climate change and climate policy when a small change in human behavior triggers large nonlinear responses in the social system. Rising global temperature above a certain threshold may trigger tipping cascades that exceed the adaptive capacity and resilience of natural and social systems, and spread through networks connections, including disasters and weather extremes, famines and epidemics, poverty and refugee movements, crimes and riots, violent conflict, and terrorist acts. These can involve drastic changes in individual and collective action, as well as in institutional settings, including changes in governance, legal and economic arrangements, and long-term effects on social norms and values.

Social tipping points demonstrate asymmetric trigger-response mechanisms across social system (e.g., economic, health, social cohesion) and scales (household, regional, country to global levels), considering systemic risks and adaptation limits (Juhola et al., 2022). Social tipping dynamics can interfere with tipping in natural systems in negative and positive ways, increasing or decreasing their likelihood, and trigger tipping cascades across multiple systems. Despite the unique ability of human agency to adapt, social tipping points pose challenges to established governance arrangements. Overstepping adaptation limits has been linked to mostly adverse outcomes where actors' values and objectives are strongly compromised. An adaptation limit is defined as a point at which an agent can no longer avoid intolerable risk through adaptive action (Dow et al., 2013). Soft limits encompass social institutions, norms, identity, place attachment, worldviews, values, and social support, which place limits on what can be pursued through adaptation. Cascading stressors and risks by sudden- and slow-onset climate-related events affect non-linear behavior and feedback dynamics within limits of adaptation. New adaptation practices go beyond incremental adjustments toward transformational adaptation involving systems change. Lack of alternative adaptation options or maladaptation may force people to out-migration to avoid being trapped in climate hotspots (Juhola et al., 2022).

Largely neglected in this research are models that analyze social tipping dynamics in climate-related conflict and cooperation within the larger framework of Earth-System Dynamics (Franzke et al, 2022). Social tipping points and cascades are shaped by cross-scale feedback in social systems and by human agency (Cash et al., 2006), suggesting a combination of system and agent models, exploring social tipping points enabling the analysis of complex interactions, including multiple entry points for

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abrupt changes (Hochrainer-Stigler et al., 2020) and multi-faceted governance. In the following, we introduce dynamic models expanding knowledge around climate, conflict and cooperation to better anticipate changes in the future.

## 3. Models of tipping in conflict and cooperation

### 3.1 Integrative framework of Earth-system modeling

Multiple pathways of climate-related tipping between conflict and cooperation can be embedded into an integrative framework of Earth-System Dynamics, connecting climate change, natural resources, human security and societal stability (Scheffran et al., 2012a,b). Each of the compartments is using specific model types, for the climate system (such as global climate models, including atmosphere, oceans, land surface and ice), natural resources (models of ecosystems, water, energy, soils, biodiversity, forests, agrosystems), human security (economic decision and optimization models, agent-based models) and societal interaction (game theory, coalition formation, multi-agent dynamics, social network analysis). While these models are well established, their interconnection is a challenge.

The couplings and interactions between the model compartments can be characterized by sensitivities that represent the impact of change in one variable on another variable (in particular, climate sensitivity and conflict sensitivity). For instance, changes in the climate system affect the functioning of ecological systems and natural resources as well as human security and societal stability. Depending on vulnerability, environmental changes stress basic human needs and security (such as the availability of resources for health and wealth). Human responses to environmental change can affect the stability of societal structures, driving migration and violent conflict, as well as networks, strategies, and institutions to avoid dangerous instabilities. Compounding events are spreading through the interconnected network, amplifying to complex crises and "syndromes".

While we do not aim here for integrated assessment modeling of these complex interactions, we focus in the following on different approaches to model tipping between conflict and cooperation in the context of climate change. There are different schools of thought and various model classes to analyze the complex dynamics of conflict and cooperation, beyond simple data-driven statistical models which lack the ability to simulate future projections (Scheffran and Hannon, 2007; Guo et al., 2018). We focus on system and agent models to discuss possible conditions for climate-related conflict and cooperation, followed by a short overview of other models for specific cases and data.

### 3.2 System models of conflict and cooperation

Sociophysical system models capture prior beliefs in how societal actors choose to behave. Following system dynamics models in ecology, for instance the Lotka-Volterra equations of predator-prey interactions developed a century ago, the models are simple and with analytical solutions, e.g., we can identify equilibria, transient behaviours, and relate their asymptotes to parameters (Pruitt et al., 2018). The choice is driven by environmental and social factors, and this can be a bi-stable model where the stable states are cooperation and conflict (see Sect. 4).

Of this type were the differential equations applied to understand conflict at the beginning of the 20th century. Shortly before World War I, the British engineer Frederick William Lanchester (1868–1946) developed mathematical "laws of warfare" to win or lose a battle based on the number and efficiency of forces (independently found by Russian mathematician M. Osipov). Around the same time the British physicist, psychologist, and pacifist Lewis Fry Richardson (1881-1953) who is well known for his important contributions to weather forecasting, applied mathematical modeling to better understand arms race and conflict, as well as predict and prevent war by finding general laws of interaction among nations (for a comprehensive review see Gleditsch, 2020). Deriving a set of linear differential equations to describe the arms build-up in World War I, Richardson projected that the arms race between major powers during the 1930s could lead to another major war (Richardson 1960a,b). The model assumes that each country increases its own armament (force) level $X_1$ proportionate to the armament of an opponent

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$X_2$ (weighted by a defense coefficient) and reduces it proportional to its own armament (weighted by the fatigue coefficient) plus a "grievance" term (measuring the readiness to arm, independent of the forces of both sides). The forces of both sides do not change when the driving and dampening drivers are in a "balance of forces". Its stability is determined by the eigenvalues of the matrix of coefficients. For a positive eigenvalue a deviation from equilibrium grows exponentially (corresponding to instability), for a negative eigenvalue it decays asymptotically (indicating stability). For two nations instability is given if the product of defense coefficients exceeds the product of fatigue coefficients, indicating that the drivers of arms-build-up exceed the constraining factors favouring disarmament. This threshold of instability and arms race can be seen as a tipping point between qualitatively different states of conflict escalation and de-escalation (Scheffran, 2020b), which are only partly reversible as military spending is lost for other purposes, even more when arms are used in warfare for destructive purposes.

Richardson's model initiated a flood of publications on the armament dynamics and a debate about its applicability to real-world conflicts which raised several critical issues, some of which Richardson was aware of (Smith, 2020). An arms race, like any conflict, does not only rely on quantitative, but also on qualitative aspects, such as perceptions and doctrines. Influencing actions in conflict based on decision rules make interaction less mechanistic and open opportunities for control and responses based on limited information about the world. Armed conflict is not only an action-reaction process, driven by the opponents' armaments, but is also stimulated by bureaucratic and budgetary dynamics with competing domestic interests. Although an arms race may provoke crisis-instability, it does not necessarily lead to war if both sides want to avoid it or one side reaches upper limits of armament which excludes an unlimited arms race.

Several extensions have been proposed to address the deficiencies of the Richardson model. Intriligator (1975) developed decision rules for increasing or decreasing weapons to bridge the gap between desired and current levels, based on strategic considerations on the expected outcome of deterrence and warfare. While the linearity and simplicity of the Richardson equations represent a few paths of system behavior (oscillations, asymptotic decay, exponential increase), its rather simple structure does not represent the complexity of reality where reactions may be disproportionate and non-linear, showing unpredictable and qualitatively different modes of behavior, such as multi-stability and tipping between them. The most immediate extension is in time-discrete difference equations with quadratic and other non-linear state-response functions explored in bifurcation and chaos theory since the 1970s, to study critical phenomena, such as self-organization, tipping points, discontinuous phase transitions, and irreversibility. The concept of chaos in armed conflict was introduced to show that simple non-linear deterministic arms race models may lead to the breakdown of predictability (Saperstein, 1984). The chaotic dynamics in arms race models was investigated by Grossmann and Mayer-Kress (1989) using security-drivers and upper cost limitations. Factors provoking chaotic behavior beyond a threshold are overshooting or underestimation, hectic responses, delay in information processing or discretization. The authors distinguish between chaotic responses and instability which contains the risk of war (Grossmann and Mayer-Kress, 1989).

While the simple two-player arms race represented by Richardson's model was a paradigm of conflict studies during the Cold War, chaos became a paradigm for the turbulent transformation and domino effects leading to its end after 1989. Current conflicts may be more adequately described by complex multi-actor dynamic models following decision rules responding to rapidly changing security conditions and violence. Not only the levels of armament are relevant for security, but also economic and technological interconnections as well as social and ecological factors, linking security and sustainability. More recent work in conflict models connects individual tipping dynamic settlement nodes together with a multi-layer interaction dynamic that tries to describe political and socio-economic ties. Using historical data on conflict and interactions, machine learning is used to fit and parametrize these models (Aquino et al. 2019), identifying multiple pathways in climate conflict research based on large-scale data globally (Ge et al., 2022) and regionally (Xie et al., 2022).

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### 3.3 Agent models of conflict and cooperation

Decision-making and agent-based modeling (ABM) capture diverse societal agents that can choose and adapt their decisions and actions based on motivation, capability, and behavioural rules, according to reasoning, learning, perception, and anticipation which affect the expected outcome of tipping. Individual agents can select from a range of options adequate to their preferences and priorities, e.g., following rules of optimization, satisfaction, and bounded rationality, dependent on environmental change and decisions of other agents in game-theoretic settings. While non-cooperative games search for solution concepts such as Nash equilibria or Pareto optima, cooperative game theory has been developed for players joining coalitions. Evolutionary game theory analyses the competition among populations via replica equations that select cooperative and non-cooperative strategies according to their fitness (Hofbauer and Sigmund, 1998). The repeated prisoners' dilemma has been used to analyze the evolution of cooperation in experimental games (Axelrod, 1984,1997), finding sequential strategies (such as tit-for-tat) which depends on the payoffs of the players and social context in which the games are played, using social learning and positive tipping to escape from social dilemmas.

Adaptive models explore the linkages between optimizing and other rule-based behavior, finding adaptive mechanisms between short-term action-reaction patterns among agents according to response strategies and coevolutionary rules. Models of artificial life and artificial societies use computer simulation to analyze complex interaction between a great number of agents who follow stimulus-response patterns in virtual environments (Epstein and Axtell, 1997). Going back to tipping in spatial segregation models of Schelling (1971) and Sakoda (1971), ABM uses behavioral rules and simulates complex multi-agent patterns of interaction, which is useful in situations of uncertainty and bounded rationality, considering the adaptive nature of human action in changing environmental conflicts (Bendor and Scheffran, 2019). Due to complexity an analytic treatment is difficult, and better understanding is required on how conflict and cooperation evolve in multi-agent settings. Climate and resource limitations may modify the rules and interactions, triggering conflictive or cooperative behavior changes.

Multiple agents show collective behavior via opinion dynamics, coalition formation, network building, social feedback, structural shifts, social norms, and transformative policies, including pathways and transitions between conflict and cooperation which can be subject to tipping (Bendor and Scheffran, 2019; Juhola et al., 2022). An example is Epstein (2002) who explored the dynamics of decentralized civil unrest and interethnic violence, which indicates tipping points for police efforts when the model produces decentralized outbursts of violence. ABM can implement complex systems dynamics, such as cross-scale interactions, non-linear processes, cascading effects in social networks, and self-reinforcing chain reactions that could e.g., increase conflicting and antisocial behavior triggering systemic risks (Filatova et al., 2016; BenDor and Scheffran, 2019). ABM captures macro-scale phenomena from micro-scale interactions among many heterogeneous adaptive and learning agents (Filatova et al., 2013) where seemingly minor events can provoke major qualitative changes in social systems, such as the end of the Cold War and the Arab Spring. A cycle of environmental degradation and hazards could lead to economic decline, possibly causing social unrest, and disruption of political institutions destabilizing affected societies (BenDor and Scheffran, 2019). ABM is applied to study agents' adaptation behavior and institutional responses to climate hazards and conflicts, bound by social structures, simultaneously generating and shaping them.

Societal interactions can also be represented by social network analysis (SNA) which can visualize the dynamic switching and tipping between alternative pathways in response to changing internal and external conditions, in particular hostile and friendly attitudes, conflict or cooperation, violence, and peace. Of great interest is the dynamic spread of cascading processes and patterns in social networks, such as the diffusion of social behavior, technical innovations and spatial conflict (e.g., Kempe et al., 2005; Flint et al., 2009; Maoz, 2010).

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### 3.4 The VIABLE model framework: Stability and complexity in conflict and cooperation

Different approaches can be integrated in the VIABLE model framework which stands for "Values and Investments for Agent-Based interaction and Learning for Environmental systems" (Fig. 2a). In short, it models the dynamic action and interaction of agents who use part of their available capabilities ($K$) as investments ($C$) with priorities ($p$) to given action pathways ($A$) that change their environment ($X$). The observed impacts of actions are evaluated in each time step based on actual values ($V$) and targets values ($V^*$) where agents are satisfied. Important parameters are the sensitivity of value to environmental change ($v_x$) and the inverse sensitivity (unit cost) of environmental change to investment ($c_x$). The respective value-cost ratio $f = v_x/c_x$ of an action indicates how sensitive and efficient its value is to investment. Negative efficiencies $f$ indicate a conflicting action path where agents violate their values in social interaction (Bendor and Scheffran, 2019). In repeated time steps and learning cycles agents mutually adapt their capabilities, action priorities and values to the satisfaction levels, as a function of the sensitivities between agents and the environment. Within the available capability limits, agents can adjust their action pathways to meet their value goals according to decision rules which determine equilibria where agents are satisfied.

The first model application was the Cold War arms race in the 1980s, where a tipping from hostile to friendly attitudes of the superpowers was simulated, showing a chaos-like transition to nuclear disarmament which was validated later. The VIABLE framework was also applied to other problems related to tipping, e.g., in fishery, land use, energy, transportation, health, sustainability, climate policy and emission trading (see Scheffran and Hannon 2007; Bendor and Scheffran, 2019).

The VIABLE model allows to study analytical conditions for transitions between states of conflict and cooperation, fixed points representing the balance of satisfaction levels and invested capabilities (social equilibrium), as well as stability and chaos. Agents can control and stabilize or destabilize the dynamic interaction by using their capabilities and changing their action priorities to achieve their target values. If the action priorities are directed towards hostile relations (damaging the values of other agents), the dynamics moves towards higher investments, corresponding to conflict escalation. On the other hand, in a bi-stable case agents can switch to mutually beneficial cooperation, lowering necessary investments. They may also be neutral in having no effect on each other's satisfaction levels or mix cases (Fig. 2b). Individual agents can also form coalitions by pooling some of their invested capabilities and redistributing the gains (or losses) to the agents, or they may agree on the same values and targets, thus moving from individual to collective or institutionalized action and interaction.

The type of social interaction is represented by the interaction matrix and its stability, mathematically determined by the eigenvalues around the social equilibrium (Fig. 2b). If agents are powerful in terms of their capabilities and efficient in pursuing their value goals, they can withstand, compensate, or counter-act a certain level of hostility by others, thus keeping eigenvalues in the negative range and avoiding major deviations from the equilibrium. If the hostile actions exceed a critical threshold, an unstable escalation may occur, leading to the breakup of the social system. Stability of social interaction can be maintained if the positive (cooperative) effects of agents on each other exceed their negative (conflicting) effects. With a growing number of agents, the complexity of the interaction matrix and the number of eigenvalues increases, including those that are potentially unstable. This is known in systems theory as the "complexity-stability" tradeoff and raises the question whether complex social systems are more stable or unstable (Scheffran and Hannon, 2007; Gravel et al., 2016). In response to tipping points and related cascades a system can break apart into simpler ones or forms more complex ones. Mutual adaptations or institutional control mechanisms can stabilize the interaction and contain conflict, e.g., by social security or other forms of government support.

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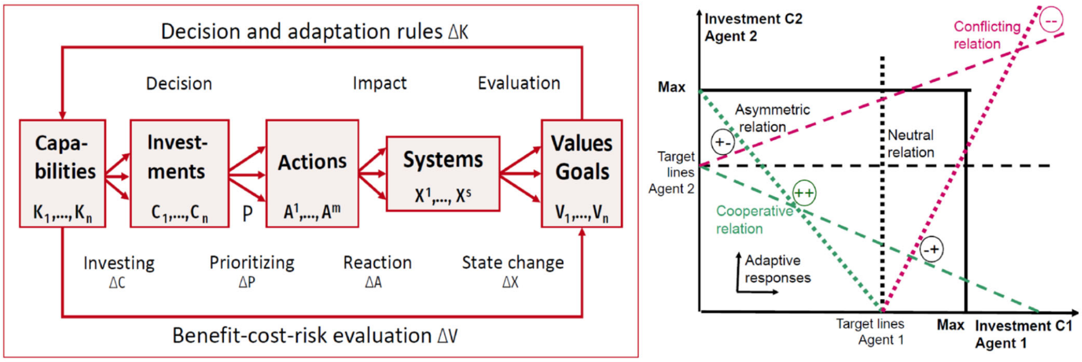


**Figure 2: (a) Dynamic VIABLE model framework for multiple agents; (b) Adaptive target lines for two agents and mutual equilibria (balance of investments) for conflicting (--), cooperative (++), mixed (+-/-+) and neutral relations.**

### 3.5 Additional models relevant for tipping in conflict and cooperation

There are various additional models for the study of tipping processes in conflict and cooperation that are specific to certain application areas, methods, and data, including nonlinear models, which are shortly referred to.

- *Causal inference models:* Sometimes there is an abundance of data, but a lack of clarity on mechanisms, pathways or differing accounts. This is problematic when we wish to develop mechanism-driven models, as we may not know what is coincidental, correlated, or causal. Indeed, even if we are clear on the mechanisms, we may not know the strength or directionality or temporal dynamics of ties. Causal inference is often a first step before models are constructed. Toy causal models that abstract complex relations are often needed first to allow us to see if causal inference methods can be successful, before experimenting on real data. End-to-end causal inference using non-linear state or mutual information methods such as predictability improvement or convergent cross map has limited success on toy models (Guo et al., 2023). We know that climate-induced social change often has a bifurcating excitation causal process (e.g., where social transformation is not easily reversible – see Lake Chad case study in Section 5). The most recent work has integrated bifurcation and excitation behaviours with neural networks to harmonize data driven prediction with expert-informed climate fragility indices (Sun et al., 2022).
- *Excitation-cooling processes:* Specific conflict processes are modelled within specific genres of violence such as the coupling between improvised explosive device attacks and security retaliation (Tench et al., 2016), where a successful attack leads to more attempts in the same area. Example papers covered data from Northern Ireland, Iraq, and Afghanistan. This excitation process is causally based on previous successes and can only be cooled down by security forces increasing patrols and preventions. As there are phases of excitation and cooling, with transitions driven by security interventions, one can perceive this as a special kind of tipping process.
- *Diffusion processes:* This is particularly suitable for modeling large-scale expansive conflicts across Afghanistan (Zammit-Mangion et al., 2012), Mali, Iraq etc. As the diffusion is driven by geographical attractors, it can tip the conflict diffusion in one direction or another as a spatial tipping process. These often use non-linear kernels to create a dynamic diffusion map with abrupt behaviours and can be interpreted as tipping behaviour in a spatial domain.

Bi-stable models already exist in animal ecology, where environmental factors such as food supply and temperature modulate whether insects fight or cooperate (Pruitt et al., 2018). They recognize "tipping points" through: (1) further ecological changes can no longer affect behavior in the same way as before; (2) rapid changes occur between behavior states (possibly at the brink of tipping); and (3) a significantly delayed recovery to prior states after environmental conditions improve. The early-warning signs they look for are: (a) increased variance in behavior as a signature of instability; and (b) signs of changes in other non-

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observed behavior or queues that indicate a change is imminent. Moving on to human conflict, a conceptual framework for understanding urban conflict tipping points was developed in Moser and Horn (2011). Here, quantitative, and qualitative factors/processes contribute to the tipping point (Beall et al., 2010), which can be defined as a movement or group of people taking a new trajectory towards violent mechanisms. A range of determining factors across violence genres were identified:

- Conventional (mostly statistical with narrative context): socio-demographic characteristics of youth gangs, ethnic/religious/caste profile of political classes, surge in certain crime categories and corresponding legal framework.
- Short-term tipping trigger (mostly statistical): paradigm shift in politics or public perception due to a trigger event (e.g., media event, political event, sudden surge in violence or a major economic event).
- Long-term tipping bias (statistical): long term unemployment, parental guidance, substance use

In urban violence, they also identified several case studies such as the Santiago gender-based violence, Nairobi political violence (2008), Dili factional violence (2006), Sudan (2011), and Patna riots to improve security in the city. In each of these cases, a value chain can be constructed to aid understanding of how more complex and causal tipping models can be constructed. We will review the detailed models below, as well as showcase a potential bi-stable model for conflict and how it can form part of a larger networked model to reflect global connectivity (Aquino et al., 2019).

## 4. Modeling tipping cascades in conflict and cooperation

### 4.1 Bi-Stable Tipping Models in Action

As discussed in Section 3.5, one way to conceptualize a conflict vs. cooperation model is to imagine these as two stable states, whereby being in a state means that a certain amount of "extra" energy or incentive is needed to move out of it. These are regarded as stable, and we can further regard those nations that take very little incentive to move from cooperation to conflict as fragile, and those that take a lot as being resilient. Let us briefly review alternative models of lower and greater complexity that can model state transitions (see Fig. 3):

1. *Discrete binary flip model* (e.g., Ising model), where there is a probability that independent variables will contribute to a probability of flipping between conflict and cooperation states. However, this discrete model may not capture the tension and sliding dynamics.
2. *Continuous attractor model* (e.g., Potts, Kuramoto), where there is a pull towards certain state(s) and independent variables can push or pull the state between conflict and cooperation, e.g., the current state can transition and stay between attractor states.
3. *Continuous bi-stable model* (e.g., tipping point), where two states are stable and are entropy wells (or basins of attraction), that entrap an agent within it.

In fact, the third kind of tipping model has been used in ecology to model how animals choose to cooperate or compete under different environmental stressors (e.g., temperature) (Pruitt et al., 2018). As such there is significant cross-domain modelling background to motivate our writing below.

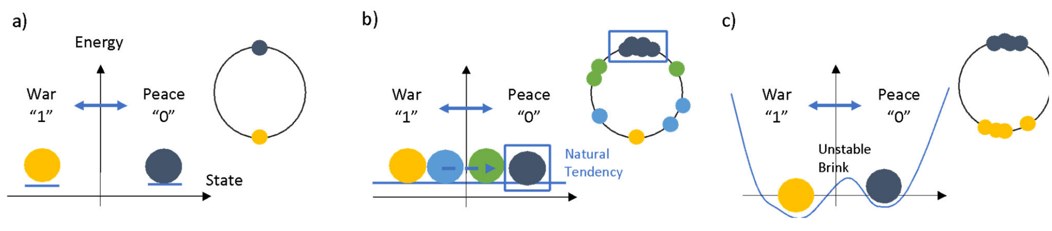


**Figure 3: Concepts in modeling tipping points: (a) flip models, (b) attractor models, and (c) bi-stable models.**

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To create the simplest model that exhibits bi-stable effects, we need to employ a third order polynomial:

$$\frac{dx}{dt} = x\left(1 - \frac{x}{C}\right)\left(\frac{x}{K} - 1\right) + F \quad (1)$$

Here, we are saying the rate of change of the dependent variable $x$ (e.g., level of cooperation), is dependent on the current value of $\boldsymbol{x}$, modulated by a Capacity $C$ term and a smaller Criticality $K$ term. An external forcing term $F$ can include many factors such as trade, political influence, online influence, and climate change. Here, we explore some critical states:

- *Growth:* the greater the current value of cooperation $x$, the more cooperation occurs, subject to the below limits of $C$ and $K$.
- *Full Cooperation* (Stable State): when the level of cooperation reaches maximum capacity ($x$=$C$), the rate of growth is 0, meaning any further growth will naturally retract back to $C$ value.
- *Minimum Cooperation* before Conflict (Unstable Tipping Point): when the level of cooperation reaches minimum criticality ($x$=$K$), the rate of growth is 0, meaning any further retraction will retract to conflict.
- *Conflict* (Stable State): when the level of cooperation reaches zero ($x$=0), the rate of growth is 0, meaning any further growth in cooperation will retract naturally back to conflict.

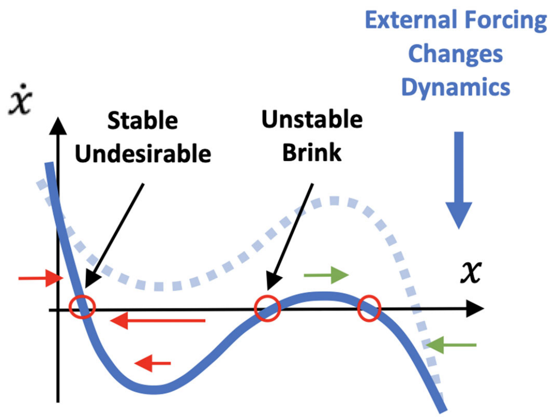


**Figure 4: Transition between stable states via tipping point:**
$\frac{dx}{dt} = \dot{x}$ **refers to the rate of change of $x$, and the unstable brink is a tipping point.**

In these tipping dynamic systems, they are primarily affected by 2 variables:

- Internal parameters ($C$, $K$) affect the fragility of tipping, e.g., how easy it is to transition between states.
- External forcing ($F$) that affect the tilt, biasing the likelihood of tipping one way over the other.

### 4.2 Cascading and self-enforcing dynamics in conflict

#### 4.2.1 Stable State Transition Scenarios

State transitions between conflict and cooperation can occur when sufficient energy drives the process. In Fig. 3, we show the equation of bi-stable systems, and we show the state transition between stable states via the tipping point (unstable brink in between). Here, we can see the horizontal red arrows indicating that in or near the undesirable conflict state, external "forces" $F$ can push the system towards conflict, and the horizontal green arrows indicating that in or near the desirable cooperation state, all forces push the system towards cooperation. The forces $F$ we refer to can be from for example climate and will move the dynamics up and down (see solid line vs. dashed line). In one example, should there be a very positive force, the dynamics

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can consequently have only 1 stable cooperation solution, removing the possibility of conflict and tipping point. Conversely, a negative force can result in only 1 stable conflict solution, removing the possibility of cooperation and tipping point.

#### 4.2.2 Cascading and self-enforcing dynamics in cooperation

One way to capture diverse external forces between different cities or countries (nodes) is to construct a graph with:

- *Nodes*: Cities or Countries are nodes.
- *Links*: Relationships are links between nodes which can have either binary data (1 or 0), or weighted data (strength of relationship). The data can be dynamic to reflect change over time and be directional to reflect unilateral relations.
- *Graph Layers*: multiple layers can reflect different types of relationships (diplomatic, military, transport, trade), and each layer can be interconnected to represent the strength of mutual coupling or cohesion.

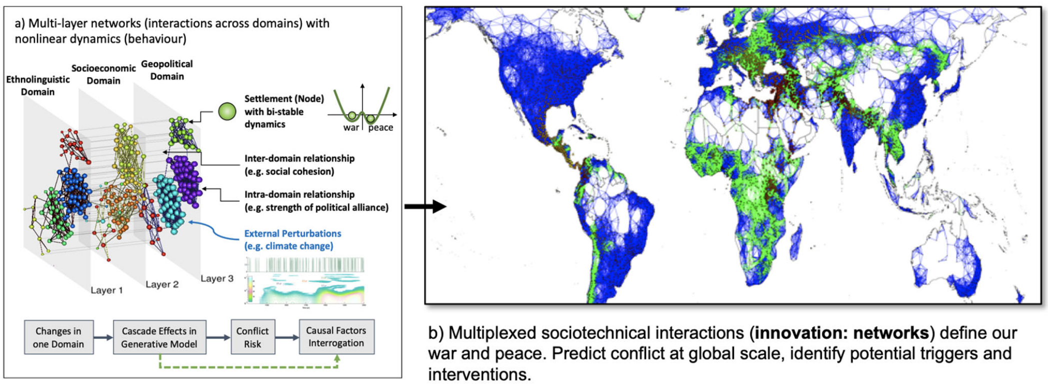


**Figure 5: Multi-layered graphs that connect local (city) tipping dynamics with inter-city relationships across ethnolinguistic, socioeconomic, and geopolitical layers. Example taken from the UK Alan Turing Institute GUARD project (Aquino et al., 2019) – funded by UK defense and security departments.**

As a result, we will create a multi-layered graph (see Fig. 5) with *N* settlements. The connected tipping dynamics for node *i* can be represented as:

$$\frac{dx_i}{dt} = x_i\left(1 - \frac{x_i}{C_i}\right)\left(\frac{x_i}{K_i} - 1\right) + \sum_j^N A_{ij}\, g(x_i, x_j) + F_i \qquad (2)$$

where the new summation term represents the graph connections (via connectivity matrix *A*) and the coupling data or function *g*(.) between attributes in node *i* and other attributes in nodes *j*. These graphs can be very large, in GUARD (Aquino et al., 2019) we have *N*=7,000-50,000 settlements, and 200,000 to 1,000,000 consequential relationship links. We use historical data to learn the parameters of the model above by fitting independent variables to the dependent variable *x*. Consistent global data across a few decades across conflict, diplomacy, trade, and transport is one of the greatest challenges.

We offer a brief review of techniques used to analyze a networked dynamical system, without going into too many details.

- *Synchronization:* This is defined by whether the whole network of bi-stable nodes can reach a single (world peace), or multiple undefined states (e.g., different alignments). Part of the proof lies in whether this even exists as it is not guaranteed for every part of the network, and a perpetual flux of state transitions is very likely, especially under dynamic perturbations.
- *Stability:* This is often defined by if there are stable states that can be reached, how rapidly can they be reached, given some initial conditions and how stable are they to further perturbations.
- *Uncertainty:* This is of interest when we wish to understand how robust is model to uncertainties in data, modeling approach, and further perturbations in the forces.

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- *Stochastic Resonance:* This may be of interest, when micro-oscillations can cause a state transition (Gammaitoni et al. 1989), where oscillations might be to do with small wet-drought patterns (see Section 5.1), or sub-threshold tension.

Due to the high-dimensional nature of the problem (e.g., number of tipping equation parameters exacerbated by the size of the graph), a range of standard assumptions are often used. At the simplest level, we assume that all nodes are at or near one of the stable states. This allows us to apply *mean field* approaches, of which the state of art is a sequential heterogeneous mean field (Moutsinas and Guo, 2020) to estimate the likely alignment between different states across the network. When we do not assume what stable state or transition between states each node is in, we must properly analyze the full dynamic possibility of the system, and this leads us into the region of attraction (RoA) method (see Fig. 6a) (Moutsinas et al., 2022). In Fig. 6b, we show how increased negative perturbations on links can pull the system towards fewer cooperation states (e.g., slide toward conflict) and eventually collapse to large-scale conflict and are unable to easily bounce back to cooperation, which we often call a loss of resilience (Moutsinas and Guo, 2020).

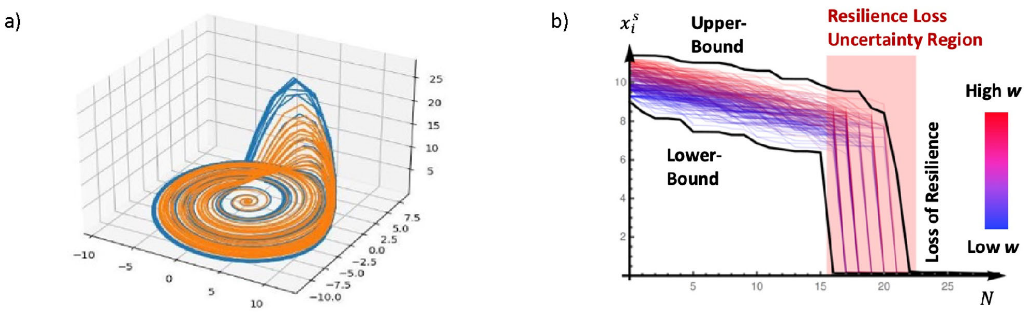


**Figure 6: State transition dynamic analysis: (a) region of attraction (RoA) analysis of networked transitions, and (b) negative perturbation on links and impact on stability of the network.**

If we are interested in how uncertainty cascades in the system, we are primarily interested in two approaches. In the first case, we assume the tipping dynamic models are representative, and only the data informed parameterization is not. In this case, we can employ methods such as polynomial chaos expansion (Moutsinas et al., 2020) or Bayesian methods to examine how different noise distributions propagate. If we are concerned that the fundamental model might be unsuitable, then we may dive into the more advanced methods of Gaussian Processes (GP) or Probabilistic Numerics (PN) to create model-free representations of tipping dynamics that can also inform evidence collection to minimize uncertainty.

## 5. Regional case studies for tipping cascades in conflict and cooperation

Following the climate-security discussion in Section 2, the review of tipping models in conflict and cooperation in Section 3 and the analysis of the transition's dynamics in the bi-stable tipping model of Section 4, we will now have a discussion of exemplary cases in regional hot spots of climate security. While this refers to key conceptions and model frameworks introduced earlier, we do not aim for a full model application of regional examples, but for illustrative cases of future in-depth research.

### 5.1 Transitions between conflict and cooperation in regional hot spots

The "risk multiplier" role of climate change is particularly relevant in vulnerable hot spot regions, such as the Mediterranean and Arctic region, the Sahel and Middle East, South Asia and Central Asia. Here it combines with other problems, including

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local degradation of ecosystems and land, absence of early warning and disaster protection, poverty, and political instability. Most vulnerable to climate stress are regions whose economies are dependent on climate-sensitive resources (water and food, forests, farmlands, and fishery) and where infrastructures are exposed to climate change, with a high dependence on agriculture, coastal areas and river basins. For the most severe consequences, adequate assistance is hardly possible and social systems become overloaded in the regions of concern. If people cannot cope with the consequences and limit the risks, tipping cascades to instability and conflict may be more likely, which may propagate through systemic networks like a domino effect or chain reaction. External aid and internal cooperation between affected communities can influence the regional tipping mechanisms in one or the other way.

Based on the bi-stable model in Section 4 we demonstrate how meso-scale groups and communities can exhibit diverse and dynamic behaviours when under climate stressors. In Figure 7a, we see that a macroscale aggregate (e.g., nation, region), can compose of several meso-scale communities (within these are individuals). Each community's behavior (or risk of behavior) can be modelled by the tipping model in Section 4, where there are 2 stable states (conflict and cooperation/peace). In these tipping dynamic systems, they are primarily affected by 2 variables:

- Internal parameters affect the fragility of tipping, e.g., how easy it is to transition between states.
- External forcing affects the tilt, biasing the likelihood of tipping one way over the other.

Here, we can see several cases (Figure 7a):

- *Blue community:* poor governance can lead to a very low barrier, allowing easy transition between conflict and cooperation (vulnerable to external perturbation)
- *Yellow community:* climate change can tilt dynamics in favour of conflict, but a healthy societal resilience (reflected in the barrier) can potentially keep the community in peace.

In Fig. 7b we can see an example community in Lake Chad, whereby it first experiences drought which seems to drive the social system to tip towards conflict, but this is not enough. The first enabling pathway is migration of fishing communities away from Lake Chad, which decreases the barrier and increases the opportunity for conflict. This opens the second enabling pathway which is that the power vacuum allows militants to move in and create conflict. The conflict between militants and remaining communities in turn raises the barrier for any return to peace, so even a return to wet season means fishing communities cannot easily return and restore peace. This relates to the following narrative of Lake Chad.

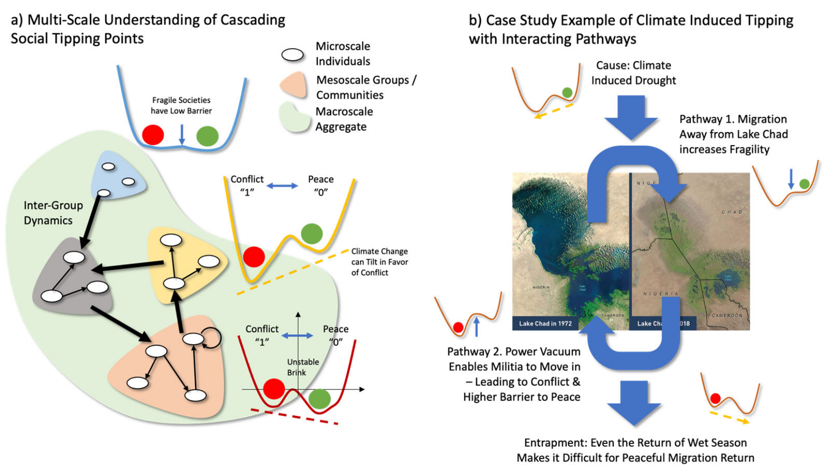


**Figure 7: (a) multi-scale understanding of cascading transitions between conflict and cooperation/peace, and (b) Example case study of climate induced tipping points with interacting pathways.**

### 5.2 Case study Lake Chad

The Lake Chad region has experienced some of the most striking social and bio geophysical changes in recent times. Just 50 years ago, the lake was larger than the size of Israel (25,000km$^2$) and provided livelihoods to over 30 million people (Gao et al., 2011; Okpara et al., 2015). Recently, only 10-20% of the lake waters remain due to rising temperatures (1.5 times faster than global average), longer dry seasons, and changes in water flow from feeding rivers. These changes, combined with megadroughts, heat waves, and sand/dust storms, have led to crop failures, livestock losses, and depletion of fisheries, and have placed the region on the edge of systemic criticality and conflict tipping pathways. The region has been afflicted by several political, identity, ethnic, communal, and resource conflict events. Most of these events have tipped over into massive upheavals in the form of terrorism, triggering brutal violence. Conflict tipping into violence under conditions of rapid lake water oscillation and shrinkage has triggered a shift from a state of relative tension to a heightened violent situation where self-perpetuating cycles of open violence become more prevalent and harmful to the Lake Chad biogeographical and ecological landscape (Avis, 2020). Conflict tipping pathways in this setting are diverse and multifaceted.

One conflict tipping pathway is the abrupt breakdown in small-scale farming, fisheries, and local food systems triggered by multi-year oscillations of the Lake Chad waters (Okpara et al., 2017). This has resulted in massive wellbeing deficits and amplified social grievances against the state. Grievances have fuelled the formation of violent solidarity networks (many with links to criminal gangs and insurgent groups) and have led to brutal regional conflicts and the death and displacement of millions of citizens.

Another tipping pathway is the escalation of a conflict economy where armed groups illegally control natural resources, agricultural trade routes, and food supply chains, and secretly divert arms, drugs, stolen cash, and cattle into areas they control (Sampaio, 2022). Armed groups recruit and radicalize young fighters who previously depended on the resources from the Lake. In doing so, they trigger spiralling territorial dynamics where the intensity and scope of conflict and violence rapidly increase. At the same time, cycles of retaliation, reprisals, and counterattacks between state and non-state actors (linked to the conflict economy) have continued to create self-perpetuating chains of violence.

Conflict tipping over into violence and terrorism harm the Lake Chad biogeographical landscape in many ways. For example, approximately 80% of the conflicts take place in nature-rich, biodiversity hotspots, and with the increasing use of the environment as a hideout, military base or camp for hostage taking, attacking the environment has apparently become a military/warfare objective (Okpara et al., 2015). Aerial and ground bombardments by soldiers primarily target the inland hardwood forests and the mangroves covering remote insurgent groups' camps, causing direct environmental damage. Similarly, the intentional bombing of villages, markets, religious centres, schools, power plants, and telecommunication facilities by insurgent groups produces many hundreds of thousand tons of emissions in carbon monoxide, nitrogen oxides, hydrocarbons, Sulphur monoxide, and $CO_2$, which adversely impact human, plant, animal, and bird populations in the region. Bomb particles contaminate water supplies in communities, undermining public health.

Conflict tipping also induces indirect harm to the Earth system. Conflict tipping triggered population displacement and complex emergencies in the region, led to overcrowding in destination areas, and intensified pressures on regional water, food, land, and energy systems (Vivekananda et al., 2019; Oginni et al., 2020; Kamta et al., 2021). These outcomes in turn spurred unsustainable agricultural practices, overfishing, and deforestation. Displaced people have turned to the environment to meet their basic needs - woods are removed regularly from forests to build shelters, make fire for cooking and heating, and to create

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charcoal for sale. Displaced people take on hunting expeditions which threaten animal biodiversity; and the wastes they produce contaminate land and water resources. Lake Chad conflict tipping (under displacement crises and growing conflict economies) is characterized by a breakdown in environmental laws and governance, causing weak enforcement of nature conservation mechanisms (Magrin, 2016). Increased illegal logging, poaching, and resource exploitation resulting from this has further exacerbated environmental degradation.

## 6. Governance challenges

### 6.1 Managing negative and positive tipping

Climate-induced conflicts require adaptive and anticipative governance (AAG) to effectively prevent and contain negative tipping to violent conflict and induce positive tipping towards cooperative solutions and synergies of climate-security risks. To stabilize climate-society interaction under deep uncertainty and complexity, diverse knowledge and deeper understanding is essential for researchers and decisionmakers about the underlying processes, how they interact and can be influenced. Besides data and experience theories and models can also contribute to tipping management and governance, including identification of drivers and barriers of tipping points, their temporal and spatial windows and conditions for stability and reachability, detectability and controllability. Appropriate indicators and instruments support adaptive decisions and responses to past, current and future tipping cascades in Integrated Earth system models.

Model scenarios can indicate tipping to conflict and how to prevent and contain escalation by political and legal measures, strengthen resilience and cohesion of societies in the long run, by enabling communities to respond to combined climate and conflict risk and avoid polarization. Managing tipping cascades considers the respective scales of decision-making, from micro to macro, which differ from the traditional sector-specific approaches. of vulnerabilities and feedback mechanism. Moving closer to windows of potential tipping, more reliable information is needed to prepare, prevent and adapt. AAG benefits from monitoring and early warning systems (EWS) that detect and indicate signals of disaster and conflict before they occur, finding pathways for desirable change (e.g., Haasnoot et al., 2019). Conditions for successful EWS are (Grimm and Schneider 2011): (a) systematic collection of event data and expert assessments; (b) data analysis based on advanced social science techniques; (c) strategic response scenarios and consequence assessments; (d) presentation and implementation of options to policymakers. EWS can facilitate preventive responses across multiple levels, networks and stakeholders to establish regulatory regimes and institutions to be in place when needed (Juhola et al., 2022), including management of disaster, crisis and conflict to limit damages once they occur.

To understand destabilizing tipping cascades, systemic risks, hazardous pathways and acceptable boundaries, different techniques can be integrated, involving system models, ABM, SNA and KI/ML to guide AAG actions. A stronger stakeholder engagement might help to design participative modeling interfaces, considering social equity and justice, as well as dimensions of political economy, power and distribution. An example is the now commercial platform Global Urban Analytics for Resilient Defence (GUARD) using data, such as the GTD/UCDP/PRIO Armed Conflict Dataset together with advanced AI/ML systems (Guo et al., 2018; Ge et al., 2022; Xie et al., 2023). Results can feed into institutional frameworks, such as the UN Climate Security Mechanism.

Whether climate stress drives a system from undesirable to favourable pathways, from conflict to cooperation, or from vicious or virtuous circles, pathways and opportunities for action consider enabling and constraining conditions. Diverging and

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competing pathways illustrate how interacting choices and actions by diverse governments, private sector and civil society can advance climate resilient development, shift pathways towards sustainability, and enable lower emissions and adaptation. There is a narrowing window of opportunity to secure a livable and sustainable future for all (IPCC, 2023). The longer mitigation is delayed, the less effective are adaptation options.

Besides predicting and avoiding negative tipping, governance opportunities for positive (desirable) tipping cascades are essential, based on norms and goals to be achieved, such as the sustainable development goals or staying within the planetary boundaries, including the climate targets in the Paris agreement. To bring a system to an intended tipping point requires some "forcing" for transformation. Since agents select actions that are more beneficial, less costly and less risky compared to alternatives, managing positive tipping cascades could apply ABM approaches such as the VIABLE framework to represent motivations and capabilities in switching to alternative pathways (in energy, food, health, etc.) and overcome path dependency, lock-ins, time discounting and established habits. For instance, in the energy transition the strong dependence of fossils requires policies to increase the benefits of renewables (e.g., by subsidies or sharing the revenues) and reduce their cost, risk and conflict potential such that a critical mass is built for a self-enforcing collective positive cascade.

Human agency can intentionally utilize trigger-response mechanisms and feedbacks in social systems to establish new norms and collective action, across scales and social systems. New adaptation practices go beyond incremental adjustments toward transformational adaptation involving systemic change (Juhola et al., 2022). Diverse sources of knowledge can help to contain this uncertainty, including scientific data and modelling as well as local and indigenous knowledge based on experience, mobilized in participatory approaches and collective learning. Agency benefits from constructive and mutually adaptive behaviour of agents to induce positive tipping in swarming interactions.

### 6.2 Conflict transformation and environmental peacebuilding

Civil conflict transformation (CCT) is nonviolent and uses only civil measures. Mediation, victim-offender mediation, conciliation, round tables and dialogue forums are prominent examples, as well as other forms of violence prevention and diplomacy, peacebuilding and civil peacekeeping. CCT can make an important contribution to dealing with climate change and the current crises of nature-society relations. Climate policy can be used as peace policy and vice versa (Pastoors et al., 2022). Conflict tipping has the potential to foster creativity and community and can create positive transformative opportunities to reconstruct societies. Conflict transformation and cooperation can facilitate this process, especially when a critical mass of conflict actors adopts new attitudes, behaviours or values. This can lead to positive social tipping effects that spill over into society. Conflict transformation deals with and transforms the immediate and deep issues people fight about, such as marginalization, abuse of human rights and widening acute poverty. By creating inclusive and equitable social structures or fostering paradigmatic events that shift the perceptions and attitudes of conflict actors toward dialogue, trust building, and reconciliation, conflict transformation can move conflicting parties from a state of confrontation and violence to one of cooperation and collaboration. Combining conflict transformation and cooperation can create a powerful synergy that leads to significant positive changes in society.

One approach to foster such conflict transformation towards cooperation is environmental peacebuilding, which focuses on managing renewable natural resources in conflict-affected areas with a conflict-sensitive and sustainable approach, aiming to promote lasting peace (Krampe et al., 2021). Research in this field is divided into two main schools: cooperation perspectives and resource risk perspectives. Cooperation perspectives prioritize collaborative approaches to managing environmental resources, aiming to promote peace-making through spill-over effects and positive peace outcomes that encompass human security and equity. In contrast, resource risk perspectives emphasize addressing resource-induced instability and sustaining negative peace through environmental cooperation (Krampe, 2017).

While quantitative studies have been conducted, there has been a notable increase in qualitative case studies, particularly emphasizing the local and everyday experiences of environmental peacebuilding (Ide et al., 2021; Johnson et al., 2021). This localized perspective is crucial, as key dynamics of environmental peacebuilding often occur at the local level. Recent studies highlighted the need to advance scholarship to better theorize the causal understanding of natural resource management in post-conflict settings (Johnson et al., 2021, Krampe et al., 2021) and of providing proof of the contribution of environmental peacebuilding initiatives to positive peace and mitigate tipping points. Krampe et al., 2021 have proposed three theoretical mechanisms to explain how environmental cooperation can contribute to positive peace: (1) the contact hypothesis posits that facilitating intergroup cooperation reduces bias and prejudice; (2) the diffusion of transnational norms suggests that introducing environmental norms supports human empowerment and strengthens civil society; and (3) equitable state service provision, which argues that providing and ensuring access to public services that address the instrumental needs of communities strengthens state legitimacy and state-society relations.

As interventions become more common, there is a growing recognition of the negative implications of environmental peacebuilding, often referred to as "backdraft", which are linked to the broader debate on maladaptation (SIPRI, 2022). Indeed, an emerging body of work sheds light on the unintended and unanticipated consequences of environmental peacebuilding interventions (Ide, 2020). Further research in this area is necessary to avoid romanticizing the concept of environmental peacebuilding and to learn from past experiences to prevent potential conflicts triggered by poorly planned and managed climate adaptation and mitigation efforts. Ideally, this research can also help identify opportunities to generate positive legacies of peace (see e.g. Simangan et al., 2023).

## 7 Summary and conclusions

This study connects the wealth of empirical research on the dynamics of conflict and cooperation under climate change with the growing research on tipping points, compounding and cascading risks, in the qualitative discussion of complex pathways, transitions and interactions of tipping in security-related issues and by a selective review and application of quantitative modeling, connecting both research fields in a novel way.

Following an introductory contexualization in complexity science and today's multiple crisis landscapes, a structured overview (Section 2) highlights that climate and environmental change can affect the relationship between conflict and cooperation, depending on certain conflict-relevant conditions and multiple risk indicators which affect human choice and societal responses triggering tipping via key pathways in the climate-conflict nexus (livelihood deterioration, migration and mobility, opportunities for militant and armed actors, grievances). Compounding effects can results from the double exposure to conflict risk and environmental vulnerability, making it difficult to separate them in a mutually enforcing and escalating vicious circle beyond critical thresholds.

Within the framing of integrative Earth system dynamics, relevant model types of conflict and cooperation are introduced in Section 3. Among more specific models we focus on system models analyzing dynamic trajectories, equilibria, stability, chaos and empirical applications to conflicts (such as the Richardson model), as well as agent models following decision rules of behavior based on motivation and capability, driving and preventing conflictive or cooperative actions. The VIABLE model framework integrates the adaptive dynamics of values, capabilities and priorities for systemic actions, providing simulations

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of conflict cases and analytic conditions of social equilibria, stability and complexity of multi-agent interaction and related tipping, cascading, networking and transformation.

An illustrative bi-stable tipping model in action is presented and applied in Section 4, to study the cascading and self-enforcing dynamics involving capacity, criticality and external forcing, and present transition scenarios between states of conflict and cooperation which depend on the levels of stabilizing and destabilizing forces. The tipping dynamics is shaped by internal factors, such as fragility and resilience, and by external factors affecting the tilt, such as trade, climate change, political and media influence. The effect of city or country networks is represented by multi-layered graphs connecting local and network tipping dynamics which show how negative perturbations on links can reduce resilience and pull the system towards less cooperation or collapse to large-scale conflict.

Within the modeling context a regional hot spot perspective on the cascading "risk multiplier" role of climate change is pesented in Section 5, using Lake Chad as a case study. Based on the bi-stable model we demonstrate how in a macroscale aggregate of nations and regions, meso- and small-scale groups and communities can exhibit diverse and dynamic behaviors under climate stress between conflict and cooperation/peace. Discussed is the effect of internal parameters on fragility and the likelihood of tipping, and how external forcing affects the tilt. For poor governance community behavior is facing a low barrier against transition, such that vulnerability to climate change can tilt dynamics towards conflict, but a healthy societal resilience serves as a barrier keeping the community in peace. This is supported by narratives for the Lake Chad, where droughts can tip the social system towards conflict, together with other pathways decreasing the barrier such as migration of communities away from Lake Chad and a power vacuum allowing militants to create violent conflict which raises the barrier for return to peace. Thus conflict tipping to violence and terrorism further undermines the chance for cooperation and exacerbates environmental degradation. Finally, Section 6 discusses how governance can prevent and contain climate-induced tipping to violent conflict and induce positive tipping towards cooperative solutions of security risks. Adaptive and anticipative governance contribute to institutional mechanisms for cooperative security, civil conflict transformation and environmental peacebuilding, creating synergies for sustainable peace. A better scientific understanding and modeling of the complex interactions can contribute to forward-looking cooperative policies to prevent violent conflict and enable stabilization of the Earth system.

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