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, conditions, pathways and societal responses in the climate-security nexus are analysed. Complex interactions between climate risks and conflict risks are connected to models of tipping points, compounding and cascading risks in the context of multiple crises. System and agent models of conflict and cooperation are considered to analyze dynamic trajectories, equilibria, stability and chaos, as well as adaptive decision rules in multi-agent interaction and related tipping, cascading, networking and transformation processes. In particular, 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 interaction networks of agents, showing how negative forces can reduce resilience and induce collapse to violent conflict. The case study of Lake Chad is used for illustration to bridge disciplines and demonstrate climate change as a risk multiplier from a modeling perspective. These models relate to realities on the ground, where governance approaches and community behaviour can either lower or raise barriers to climate-induced conflict, exemplified by forced migration and militant forces lowering barriers and chances for cooperation. Adaptive and anticipative governance based on integrative research and agency are discussed to 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. Introduction: Complexity challenges in security, conflict, and multiple crises

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 a world of disorder and multiple crises 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 stability. A particular form of social instability contributing to crises is conflict between 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, systems dynamics and modeling approaches have played only a marginal role in the analysis of transitions between conflict and cooperation and related switching of behaviour. Micro-macro transitions in international security and multi-scale self-organisation may accelerate beyond tipping points. In an interconnected world at the edge of chaos (Kavalski, 2015), changes in one part of the world can have significant impacts elsewhere and propagate through systemic networks like a domino effect or chain reaction with multiplying consequences.

A scientific understanding of the underlying complex interactions is a prerequisite to stabilise the Earth system and develop forward-looking adaptation policies that prevent violent conflict and enable cooperation. This is one of the first studies that

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connects research on conflict and cooperation in climate change with research on tipping points, compounding and cascading risks. While the first field has been addressed mostly by quantitative statistical analysis of large-scale data or case-based qualitative research, the second field is rooted in conceptual and modeling approaches of tipping cascades, including system and agent-based models. Bridging perspectives and methodologies of natural and social sciences in both fields is challenging and promising at the same time. In a world of multiple crises aggregating into a polycrisis one discipline alone cannot represent the complexity of interconnected security issues (Scheffran, 2016; Homer-Dixon et al., 2022; Lawrence et al., 2024). Addressing research questions on conditions for stability and instability across the conflict-cooperation spectrum, and the role of adaptive and anticipative governance, we aim to demonstrate the relevance of tipping cascades from different perspectives and discuss alternative outcomes of positive tipping including peacebuilding and cooperation.

After the introduction on complexity challenges in today's crisis landscapes, Sect. 2 presents key terms related to compound risks, tipping points and cascades, as well as conflict and cooperation in socio ecological systems. Sect. 3 draws on a selective overview of the literature on climate change as a risk multiplier, the environment-conflict nexus and pathways connecting climate-related vulnerability, violence, and tipping cascades between conflict and cooperation in regional hot spots, as well as linkages between environmental cooperation, positive tipping, and agency. A focused review of models on conflict and cooperation and related tipping dynamics is given in Sect. 4, preparing the design of a bi-stable model framework in Sect. 5 for integrating tipping processes in conflict-cooperation studies. Model applications in climate conflict analysis are illustrated for the case study of the Lake Chad hot spot in Sect. 6. Challenges of governance and management of negative and positive tipping in conflict and cooperation are discussed in Sect. 7, including conflict transformation and environmental peacebuilding, followed by a summary, discussion and conclusions. Our study goes beyond a review of the research literature by merging complementary research streams and presenting potential pathways towards future research.

2. Compound risks, tipping points, 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 are adequate to learn about interactions and transitions between conflict and cooperation.

2.1 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 across temporal and spatial scales. Compound weather/climate events are defined "as the combination of multiple drivers and/or hazards that contributes to societal or environmental risk" (Zscheischler et al., 2018; Zscheischler and Raymond, 2022; Pescaroli et al., 2024). Risks of hazards are a function of exposure, vulnerability, and adaptive capacity of affected systems and populations which can interact in complex ways. A key risk factor is weather which comprises short-term atmospheric phenomena (e.g. rainfall over several days) and extreme events (e.g. storm, flood, and heat of certain intensity or duration), while climate refers to long-term conditions reflected in the mean and variance of data over decades (Dahm et al., 2023). There are numerous examples in fragile countries where exposure to weather-related hazards affects societies with high vulnerability and low adaptive capacity, compounding into disasters (e.g. Indus floods in Pakistan or tropical storms in Mozambique). They can also overwhelm adaptive capacity in wealthy countries, such as hurricanes in the United States where heavy rainfall and storm surge compound in devastating damage in urban centers (e.g. Katrina in 2005, Sandy in 2012, Harvey and Irma in 2017). Heavy snowfall in parts of Germany in November 2005 caused power outages for

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some 250,000 people for several days, and a snowstorm in North America 2013/2014 major power cuts for hundreds of thousands of people, leading to partial failure of communication and transport systems (Scheffran, 2016). Major floods in Western Germany in July 2021 demonstrated that unpreparedness can leave more than hundred casualties, cause billions of Euros in damage and devastate the infrastructure. When short-term weather shocks occur more frequently and intensely with climate change, they can turn into a long-term force threatening ecological and social systems that cannot adapt, damaging infrastructures and coastal protection, and provoking behavioural changes when living and working conditions become unbearable. Large-scale events such as the vegetation fires in the summer of 2010 in Russia with severe air pollution and impacts on crops and human health (Reichstein et al., 2021), affect global food markets, social stability and conflicts. Tradeoffs and synergies of compound effects are represented in the nexus approach, such as the water-food-energy nexus (Albrecht et al., 2018; Mabhaudhi et al., 2024) or the climate-conflict-migration nexus (Brzoska and Fröhlich, 2016; Watson et al., 2022).

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2.2 Tipping points and thresholds

A well-known phenomenon from chaos theory is the sensitivity to initial conditions, symbolized by the butterfly effect when small changes can have large effects which at critical thresholds to instability and bifurcation (Scheffer 2009) may trigger or prevent a phase transition into new states that do not have to be self-enforcing and irreversible. A related concept is tipping point which according to Milkoreit et al. (2018: 9) 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." 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; 2023). Above a critical temperature threshold, amplification effects and chains of events could lead to fundamental Earth system changes reaching planetary boundaries in the Anthropocene (Steffen et al., 2018). With the broad definition of tipping points they cannot only be found in natural systems but also in social systems (Otto et al., 2020; Franzke et al., 2022; Juhola et al., 2022, Mey et al., 2024). 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). Differences of social tipping are critically emphasized, such as agency, complexity, non-reductionist or non-deterministic mechanisms which can apply to both negative and positive tipping processes, depending on the evaluation of advantages and disadvantages (for critical perspectives see Milkoreit, 2023).

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2.3 Cascades and chain reactions

Tipping points may trigger more tipping points, leading to "tipping cascades", including domino effects and chain reactions (AghaKouchak et al., 2018; Klose et al., 2021; Lenton, et al., 2023). While a tipping point usually refers to exceeding a threshold (the first domino falling), tipping cascade represents the chain sequence of following events (more dominos falling). The difference is not always clear or easy to distinguish because it depends on case-specific circumstances, including the couplings of system variables and agent responses (the length, density, number of dominos and possible blocking interventions). Individual systems or communities can have a tipping point, but as the effects of tipping variables are inducing changes in other variables the question is how far the chain continues and is spreading through the network of connections and sensitivities, extending a single tipping into a tipping cascade until a new stable state is reached. Since transient behaviour is hard to predict and control, we cannot simply say whether the whole system tips or only parts of it. How far the spreading of dominos continues, when it stops or is recovered, depends on the heterogeneity and connectivity in space, time and context (for more on definitions see Lenton et al., 2023; Kopp et al., 2016).

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An example from biology and health is the Corona pandemic, in which all humans are part of a spreading virus infection with tipping and cascading mechanisms beyond a critical infection rate. A physical example is the exponential chain reaction of nuclear fission beyond critical mass or density, which is uncontrolled in the atomic bomb and held at the threshold of criticality in the nuclear reactor by control rods to extract energy. When control is lost, a reactor accident can set in motion local and global impact chains, as demonstrated by the nuclear disasters at Chernobyl (26.04.1986) following an accident, and in Fukushima (11.03.2011) when a tsunami flooded parts of the Japanese coast, claimed many lives, and triggered explosions in several nuclear reactors, spreading radioactivity globally through the atmosphere and the ocean. The consequences affected the Japanese power grid, the nuclear industry, stock markets, oil prices and the global economy when automobile manufacturers and electronics companies cut back production because important components were not delivered from Japan. The shock waves demonstrated how a compound event can set into motion a global tipping cascade, changing the economic and political environment, for instance triggering the energy transition in Germany (Kominek and Scheffran, 2012).

Revolutions in history were often associated with loss of control by the existing order and following tipping cascades, such as the French revolution following the storming of the Bastille on July 14, 1789 which destabilized the order of Absolutism. Two hundred year later, the fall of the Berlin Wall on November 9, 1989 triggered a cascade of dissolving political regimes in Eastern Europe which marked the collapse of the Soviet world order, German unification and the end of the Cold War, induced by Mikhail Gorbachev's failed attempt to reform the Soviet Union which lost control. This tipping point in world history opened the following complex era of crisis and transformation toward a globalized international system that continues to be unstable (Scheffran, 2008). A tipping cascade also evolved from the financial crisis reaching a climax with the bankruptcy of Lehman Brothers on September 15, 2008, and a subsequent international banking crisis, powered by dubious speculations, lending practices of financial institutions and short-sighted human behaviour, escalating responses and self-reinforcing interaction between rating agencies and government measures. This created an explosive situation, pushing the global financial system to the brink of collapse (Barrell and Davis, 2020). Production losses, bankruptcy of companies or stock market crashes propagated across global networks and markets, diverting hundreds of billions of dollars of state funding for stabilization. In Europe, the global economic crisis was followed by a crisis in southern Europe, particularly in Greece.

2.4 Tipping cascades in conflict and cooperation

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, escalating the conflict by continued actions, 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 to others, leading to mutual gains that stabilize this interaction. 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) which have direct and indirect impacts on human actions and responses. This interaction can lead 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 negative and positive tipping points when interaction is qualitatively changing (Spaiser et al., 2024; Eker et al., 2024; Lenton et al., 2023, Chapt. 2.4 and 4). 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 and transitions between conflict and cooperation.

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Major violent events are often related to cascades marked by initiating dates such as World War 1 (28.07.1914), World War 2 (01.09.1939), terror attacks on the world trade center (11.09.2001), Russia-Ukraine war (22.04.2022) or Hamas-Israel war in Gaza (07.10.2023), each of which was pre-empted by a sequence of events building up to decisions launching violent acts and followed by the consequences and responses. Combinations of compounding and cascading dynamics do not necessarily require a particular tipping date but can include a sequence of events over longer time periods which occur in many armed conflicts around the world. What they have in common is that the affected world after conflict tipping is perceived as different than before, which does not exclude that the dynamics can be influenced towards escalation and more violence or to deescalation ending it, pointing to the relevance of agency preventing or reversing the mechanisms of violence.

3. Crises, conflict and cooperation in climate and environmental change

3.1 Climate change as a risk multiplier

Rising global temperature above a certain threshold may exceed the adaptive capacity and resilience of natural and social systems, trigger tipping cascades and spread through networks of connections, including disasters and weather extremes, famines and epidemics, poverty and refugees, crimes and riots, violent conflict and terrorism. There can be drastic changes in individual and collective action, interference with institutional settings and governance, legal and economic arrangements, and long-term effects on social norms and values. Tipping in natural systems can interact with social tipping dynamics in negative and positive ways, and trigger tipping cascades across multiple systems (Lenton et al, 2023). Cascading stressors and risks by sudden- and slow-onset climate-related events work at different temporal and spatial scales where long term disaster acts as a general inclination to tip and short term disaster is more a force in one way.

Climate change can interact and multiply with other risks and crises, potentially leading to a downward spiral where abrupt and extensive climatic changes and extreme events could spread through global supply chains and aggravate economic shocks, stock market crashes, loss of production, supply shortages and price increases (Levermann, 2014; Sun et al., 2024). These could trigger cascades in social networks, in protest movements, elections, revolutions, mass migrations or violent conflicts (Kominek and Scheffran, 2012). Sometimes switching results from triggering events or social movements with self-enforcing cascading sequences, e.g., when an action taken by one actor provokes more intense actions by other actors. The key question is whether climate effects and related shocks are strong enough to result in tipping (Kopp et al., 2016) which dependent on specific circumstances such as resilience, cohesion and mutual support between communities. Some societies may have low, others high barriers to tipping, e.g. from societal organisation or mutual support (see Sect. 5).

An extensively discussed case is the Arabic Spring of 2011, a series of social-political protests that provoked regime change in countries of the Middle East and North Africa (MENA). The self-immolation of Mohamed Bouazizi in Tunisia on December 17, 2010 became a tipping point of uprisings spreading to Libya, Egypt, Syria and Yemen, multiplied and accelerated by the Internet and social media (Kominek and Scheffran, 2012), which enabled and motivated others to join the protest movement. Facing repression from the regime, the self-organized resistance remained largely peaceful but the situation turned violent, especially in Libya and Syria. Some sources suggested a link with the sharp rise in food prices at the turn of 2010–2011 and that extreme weather events might have contributed to these processes (Johnstone and Mazo, 2011), such as drought in Russia and China 2010 and 2011, which exerted pressure on the international market price of wheat and influenced the availability of food products. This coincided with other factors that increased food prices, including high oil prices, bioenergy development, and speculation on food markets. The consequences affected much of MENA with large food imports where low incomes and

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high food spending affected food security. The sharp rise in bread prices magnified the existing public dissatisfaction with the governments and triggered political protests. While no relevant protests took place in Israel or the Gulf States, governments in Tunisia, Libya and Egypt were overthrown, while in Syria and Yemen civil wars emerged, each with a cascade of consequences from refugee movements to terrorism reaching Europe. In this complex pattern of overlapping stressors, climate change was not the main cause, but contributed as an additional stressor overwhelming government control. The political upheavals affected the stability of the Mediterranean region but have also induced cooperative mechanisms of energy and climate governance (Lenton et al, 2023: Sect. 2.4.4.4; Açıkalın and Erbil, 2017).

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3.2 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 and 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. Competition, grievance, or greed can arise from 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 may impede the capacity of 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)" (IPCC, 2022: 12). 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 in a spiral of violence and amplify cascading crisis events beyond critical thresholds connected through tele-coupling (Franzke et al., 2022).

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3.3 Pathways of climate-security interaction

First, we consider climate change as 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 or measures to prevent and address climate risks. 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) or different types of conflict (e.g., communal, rebel, farmer-herder conflicts). Conflict parties can be nations, individuals, parties, companies, trade unions, activist groups and generations, among others.

Understanding the relationship between climate change and security risks has advanced significantly in recent years (Uexkull and Buhaug, 2021; Pacillo et al. 2024). 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 cooperate and keep 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). A substantial body of qualitative and quantitative studies from various disciplines provide new insights into the context, timing, and spatial distribution of climate-conflict risks (Buhaug, 2015; Abrahams and Carr, 2017; Scheffran, 2020; Hendrix et al., 2023; Buhaug et al., 2023). Climate change is not the sole cause (Mach et al., 2019; Sakaguchi et al., 2017; Scartozzi 2020; Ge et al. 2022), but can undermine 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 and Mobjörk, 2017; Koubi, 2019; Saraiva and Monteiro, 2023; Conca and Dabelko, 2024). The main purpose is not to prove a general and significant impact of climate change on conflict but to understand the sensitivities connecting them in both directions and the role of cooperation as a possible response mechanism mitigating climate conflict which supports complex transitions and tipping.

Research has identified five risk dynamics that illustrate the complexity of climate-related security risks (SIPRI 2022):

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 new risks that would not have existed without the previous ones.
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.

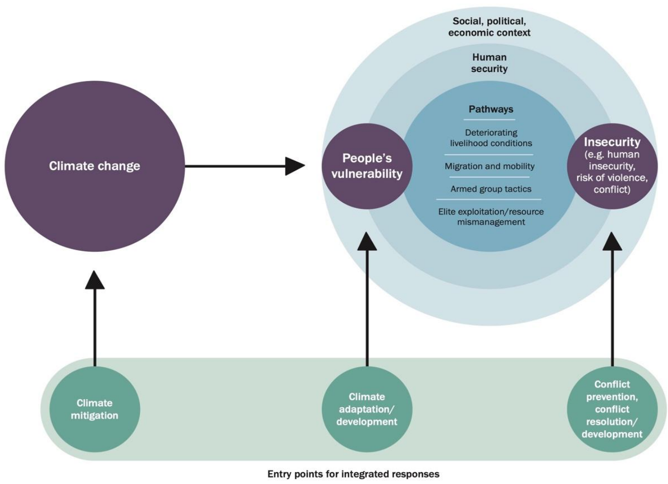

Figure 1: Pathways and entry points of climate-security interaction (source: SIPRI, 2022: 63)

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These pathways indicate the complexity of climate-related impacts on societies which reduce the system to its core elements "climate change", "people's vulnerability" and "insecurity" (SIPRI, 2022) connected through four climate-security pathways, translating climate-related vulnerability into physical violence (Fig. 1): (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).

1. Climate change undermines the livelihoods of societies, potentially 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 may lead to tensions and violent conflicts between different groups, particularly at the local level. 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 (Sheik Dahir, 2023). 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 personal needs.

2. Climate impacts and conflict risks may result in displacement and changing mobility patterns, sparking controversies and threat perceptions (Issa et al., 2023). Counterproductive responses extend security policy to fight symptoms and not causes, discouraging migration, stigmatising displaced populations, and tightening border controls. Migration decisions of exposed populations depend on personal and social circumstances (Koubi et al., 2022). There is a tradeoff between motivating drivers of migration and diminishing capability to move, leading to involuntary "trapped" populations (Benveniste et al., 2022). While migration under climate and conflict may entail exposure to new risks, it can reduce some risks and serve as an adaptation and risk management strategy (e.g. Gioli et al., 2016; Adger et al., 2024), also raising critical questions (Vinke, 2020). For instance, floods, droughts and deteriorating living conditions may drive people to urban or rural areas with limited economic opportunities, further straining local resources and causing tensions. On the other hand, adaptation can reduce incentives to move, especially in dryland regions with large seasonal and annual variations in environmental conditions. When nomadic populations move into new regions due to seasonal shifts and their herds graze on land cultivated by sedentary farmers, this may disrupt traditional mechanisms that have regulated the coexistence of these groups in the past (Bukari et al., 2018). In many cases environmental impacts are linked to temporary, short-term, or domestic migration (Hoffmann et al., 2021). Future research can develop holistic perspectives and synergies of management strategies (Simpson et al., 2024).

3. Climate change influences the behaviour 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 can affect governance structures and exacerbate governance challenges. Climate impacts can strain government capacity and resources, leading to weakened 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.

Interacting pathways and tipping cascades can create highly complex climate-conflict relations difficult to contain or control in time, space and extent. An integrated framework combines various perspectives – political and economic, social, human

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and psychologic, governance and institutions, social-ecological and environmental security. Multicausality of conflict and cooperation and feedback to climate complicates the picture. For instance, when conflicts escalate, exhibiting a tipping dynamic, they can in turn impact the Earth System environment, as warfare is producing excessive greenhouse gas emissions (Vogler et al., 2023), which is the case for Russia's war in Ukraine (Flamm and Kroll, 2024).

3.4 Pathways and tipping cascades between climate conflict and cooperation in regional hot spots

The "risk multiplier" role of climate change and climate–security pathways have been studied in vulnerable hot spots around the world, such as the Mediterranean and Arctic region, the Sahel and Middle East, South Asia and Central Asia, which serve as exemplary cases for complex social interactions and tipping cascades, dependent on regionally specific mechanisms that induce or prevent tipping in conflict. Here climate stress combines with other problems, including local degradation of ecosystems and land, absence of early warning and disaster protection, poverty and political instability (Rodriguez et al., 2019). Most vulnerable are regions whose economies depend on climate-sensitive resources (water, 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 and propagate through systemic networks like a domino chain. External aid and internal cooperation between affected communities can influence the regional tipping mechanisms in one or the other way. Most studied are climate-conflict risks on the African continent (called streetlight effect) (Adams et al., 2018). For instance, in the Lake Chad region climate extremes interact with water and food security, resource exploitation and arms transfers, perpetuating cycles of violence and displacement on the edge of systemic criticality and conflict tipping (see the case study in Sect. 6). As increasing attention is paid to other regions, key mechanisms inducing or preventing tipping in conflict are discussed here for Syria and South Asia.

The Syrian civil war has been considered as a striking case for social tipping points and cascades of security risks, conflicts and refugees affecting the stability of the Mediterranean. Before the Syrian uprising in 2011, the most severe drought was recorded in the Fertile Crescent which according to Kelley et al (2015) contributed to the loss of livelihood of farmers, agricultural degradation and rural-urban migration, linkages that remains contested (Selby et al., 2017; Ide, 2018; Dinc and Eklund, 2024). Compounding with other conflict drivers (Arabic Spring, neoliberal reforms, dissatisfaction with Assad regime, aftermath of Iraq war and Islamic State, bad governance, military response, forced displacement) the situation erupted in a violent conflict. The escalating conflict dynamics spread to neighbour regions and beyond, involved rivalling powers and moved a large number or people towards Europe. This resembled a tipping cascade of interacting multiple drivers, challenging European politics in a polycrisis of displacement, terrorism, nationalism, populism and other crisis drivers beyond Syria.

Facing low development, dense population and a substantial dependence on agriculture, South Asia is particularly sensitive to climate change and its extremes (Wischnath and Buhaug, 2014). At the same time, the number of armed conflict events has increased from 1850 in 2000 to 2846 in 2015, where most events occurred in Afghanistan, Sri Lanka, Nepal, Pakistan-Afghanistan border, and the seven Northeastern states of India (Xie et al., 2022). According to this source, precipitation can impact armed conflict via direct and indirect pathways which are contradictory in sign, while temperature affects armed conflict negatively through a direct path and indirect effects were insignificant. Involving the intermediary variables water resources, crop yield and income, net combined impacts are weak due to two contradictory effects offsetting each other which indicates no clear sign of self-enforcing tipping points. Under ~~unfavourable~~ weather conditions with substantial crop yield reduction and economic losses, violence might become a source of income for those who cannot live on rain-fed agriculture, food supply, or

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6.1 Transitions between conflict and cooperation in regional hot spotThe "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. …ere climate stress it …ombines with other problems, including local degradation of ecosystems and land, absence of early warning and disaster protection, poverty,…and political instability (Rodriguez et al., 2019). Most vulnerable to climate stress …re regions whose economies depend on climate-sensitive resources (water, 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 and propagate through systemic networks like a domino chain. External aid and internal cooperation between affected communities can influence the regional tipping mechanisms in one or the other way. We use selective examples from three different regions to identify key mechanism inducing or preventing tipping in conflict. ¶
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livelihood security. Contradictory interactions may occur at country level where adaptation and mobility in agriculture mitigate climate and conflict risk (Abid et al., 2015; Mobeen et al., 2023). A case study explored how smallholder villagers in Tamil Nadu, India, are managing systemic livelihood risks by sea level rise, coastal inundation, droughts and flooding by cyclonic storms, preventing tipping points and inducing deliberate transformational change (Mechler et al., 2019; Juhola, et al. 2022).

3.5 Environmental cooperation, positive tipping, and agency

Tipping in climate-conflict risk dynamics is not deterministic but influenced by context, conditions and agency. Human ability to adapt relies on norms, governance and institutions. Beyond adaptation limits agents may no longer avoid intolerable risk (Dow et al., 2013). New practices prevent maladaptation, go beyond incremental and toward transformational adaptation (Juhola et al., 2022). Not only conflict is a possible response but also cooperation – e.g., when governments and societies build alliances around environmental challenges, or initiate agreements and policy frameworks along shared goals, building trust and social cohesion (Huitema and Meijerink, 2018). Mutual adaptation of actions or institutional mechanisms can stabilize the interaction, contain conflict or contribute to environmental peacebuilding. In mixed cases violent conflicts do not preclude cooperation and co-existence between conflict parties (Bukari et al., 2018). A transition from conflict to cooperation can include positive tipping cascades that shape (and are shaped by) human responses, climate policies and negotiations.

Cooperation among nations is essential for effective climate policies in adaptation, mitigation and technology transfer. International climate agreements, such as the UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement, are examples of cooperative governance at global level (Bodansky, 2016), building solidarity with the most climate vulnerable people and countries. Cooperation also happens at regional and local levels, where stakeholders build partnerships among governments, businesses, and civil society to foster innovation, promote renewable energy or implement climate adaptation (Pattberg and Stripple, 2008; Barquet et al., 2024). Collaborative governance can mobilize synergies in knowledge-sharing and capacity-building for policy implementation.

The situation is complicated by human and political responses against climate impacts which can lead to tensions over mitigation and adaptation, disaster management and damage limitation, climate geoengineering, the (un)fair distribution of costs, risks, and benefits of climate change and climate actions which require climate policies that are conflict sensitive (Nadiruzzaman et al., 2022). With increasing warming, these dynamics might become more conflictive (Victor, 2011). Countries have divergent views on climate mitigation and vulnerability, as well responsibility, technological and financial capacity, leading to disagreements that can block international climate negotiations. Within countries, conflict can arise between different economic sectors, e.g., between fossil fuel-intensive industries and renewable energy proponents, or between environmental and economic advocacy. In conflict zones, economies thriving on the extraction of mineral/environmental resources can hinder the adoption of climate policies, leading to policy gridlocks or delays in decision-making.

Largely neglected in this research are models that analyze 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 human agency (Cash et al., 2006), combining system and agent models to explore and enable the analysis of complex interactions and multi-faceted governance (Hochrainer-Stigler et al., 2020).

4. Models of tipping in conflict and cooperation

Modeling of tipping dynamics in 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). Climatic changes affect the functioning of ecological systems and natural resources which stress human health, wealth and security. Compounding human responses such as migration, conflict and cooperation, and tipping cascades are spreading through the network of sensitivities affecting systemic stability in natural and social systems. Beyond integrated assessment, we focus on system and agent models of tipping between conflict and cooperation in the context of climate change.

4.1 System models of conflict and cooperation

System dynamics models are used to study behaviour, equilibria and stability in ecological systems, for instance the Lotka-Volterra predator-prey equations developed a century ago (Pruitt et al., 2018) which can be combined with a logistic growth function to represent two stable states (bi-stability) (Sect. 5). Of a similar type were the differential equations applied to understand conflict at the beginning of the 20th century, e.g., the "Lanchester Laws" of coupled ordinary differential equations based on the number and efficiency of forces; or the general laws of conflict dynamics and arms race by Lewis Fry Richardson (1881-1953) (Richardson, 1960a,b). Central is the stability of equilibria (balance of forces), which is determined by the eigenvalues of the matrix of driving and dampening coefficients. A positive eigenvalue represents an exponentially growing arms race (corresponding to instability), a negative eigenvalue asymptotic stability of force levels including disarmament. This stability threshold corresponds to a tipping point between qualitatively different states of conflict escalation and de-escalation, which are partly irreversible as military spending and casualties in war are lost.

Richardson's model initiated research on the armament dynamics and its applicability to real-world conflicts (Gleditsch, 2020). Intriligator (1975) incorporated strategic considerations on the expected outcome of deterrence and war. Others included non-linearity and critical phenomena, such as self-organization, multi-stability, tipping points, 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 a logistic bi-stable arms race model was investigated by Grossmann and Mayer-Kress (1989) using security-drivers and upper cost limitations, distinguishing between chaotic responses and instability which contains the risk of war. While the two-player arms race of Richardson or game theory were paradigms of conflict studies during the Cold War, chaos theory became a paradigm for the following turbulent transformation and domino effects described by complex multi-factor dynamic models with decision rules responding to changing security conditions, including socio-economic, political, technological and ecological dimensions.

4.2 Agent models of conflict and cooperation

Agent-based modeling (ABM) captures 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 dynamics. 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. This helps to analyze the evolution of cooperation in experimental games (Axelrod, 1984,1997), finding sequential strategies (such as tit-for-tat) according to payoffs and social context, using social learning and positive tipping to escape from social dilemmas. Adaptive models implement rule-based behaviour of agents, including response strategies, coevolutionary rules and action-reaction patterns, as well as artificial randomness. Models of

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artificial societies use computer simulation to study complex interaction between many agents who follow stimulus-response patterns in virtual environments (Epstein and Axtell, 1997). Building on tipping in the spatial segregation models of Schelling (1971) and Sakoda (1971), ABM uses behavioural rules and simulates multi-agent patterns of interaction, which is useful in situations of uncertainty, bounded rationality, and adaptive human action, providing a better understanding on how environmental conflict and cooperation evolve in multi-agent settings (Bendor and Scheffran, 2019). Climate and resource limitations may modify the rules and interactions, triggering conflictive or cooperative behaviour changes. Ultimately agents choose behavioural rules which create social and environmental conditions affecting these rules.

Multiple agents show collective behaviour via opinion dynamics, coalition formation, social networking, norm building, and transformative policies, including pathways, transitions and tipping between conflict and cooperation (Bendor and Scheffran, 2019; Juhola et al., 2022). For instance, Epstein (2002) finds tipping points for police efforts against civil unrest and interethnic violence. ABM can simulate cascading effects in social networks, and self-reinforcing chain reactions that could e.g., increase conflicting and antisocial behaviour (Filatova et al., 2016; BenDor and Scheffran, 2019). ABM captures macro-scale phenomena from micro-scale interactions among 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 Arabic Spring. ABMs can also model environmental conflict and cooperation, as well as adaptation behaviour and institutional responses to climate-conflict risks. Societal interactions can be represented by social network analysis (SNA) which visualize the dynamic switching and tipping between alternative pathways in response to changing internal and external conditions, in particular hostile and friendly behaviour. The cascading spread in social networks has been applied to the diffusion of social behaviour, technical innovations and spatial conflict, in particular in World War I (e.g., Kempe et al., 2005; Flint et al., 2009; Maoz, 2010). Rodriguez et al. (2021) combined ABM and SNA to analyse conditions for changing mobility patterns in pastoral groups. ABM work has increased in many directions of social sciences and conflict studies to inform policy makers (Bendor and Scheffran, 2019: Chapt. 6).

4.3 The VIABLE model framework: Stability and complexity in environmental conflict and cooperation

System and agent modeling are integrated in the VIABLE model framework which stands for "Values and Investments for Agent-Based interaction and Learning for Environmental systems" (Fig. 2a) (Bendor and Scheffran, 2019). 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 each other's values. In repeated time steps and learning cycles agents mutually adapt their capabilities, action priorities and values, as a function of the sensitivities between agents and the environment. Within available capability limits, agents adjust their action pathways to meet their value goals according to logistic decision rules which determine multiple equilibria where agents are satisfied.

The first model application was the Cold War arms race in the 1980s, where tipping from hostile to friendly attitudes of the superpowers was simulated, showing a chaos-like transition to nuclear disarmament which was validated when Cold War ended. The VIABLE framework was also applied to other tipping problems, e.g., in fishery, land use, energy, transportation, health, migration, sustainability, climate policy and emission trading (Bendor and Scheffran, 2019). The model allows to study transitions between conflict and cooperation as bi-stable equilibria of satisfying investments. Agents can control and stabilize

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or destabilize the dynamic interaction by using their capabilities and changing their action priorities to achieve their target values. If action priorities are directed towards hostile relations (damaging the values of other agents), the dynamics moves towards increasing investments and conflict escalation. In a bi-stable case agents can switch to mutually beneficial cooperation with less investments. They may also have no effect on each other's satisfaction levels (neutrality) or mixed cases (Fig. 2b). Individual agents can form coalitions by pooling some of their invested capabilities and redistributing the gains (or losses), or agree on the same values and targets, thus moving from individual to collective or institutionalized action and interaction.

Social interaction in the VIABLE model is represented by the interaction matrix and its stability, mathematically determined again by the eigenvalues around the investment equilibrium (Fig. 2b). If agents are powerful in terms of their capabilities and efficient in using them to pursue their value goals, they can withstand, compensate, or counter-act a certain level of hostility by others, keeping eigenvalues in the stabilising (negative) range and avoiding major deviations from equilibrium. If hostile actions exceed a critical threshold, a destablising escalation may occur. Stability of interaction can be maintained if the positive (cooperative) effects of agents on each other exceed their negative (conflicting) effects which is a tipping condition. With a growing number of agents, the complexity of the interaction matrix and the number of eigenvalues increases, including those that are potentially unstable, which is known in systems theory as the "complexity-stability" tradeoff (Gravel et al., 2016). In response to tipping 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.

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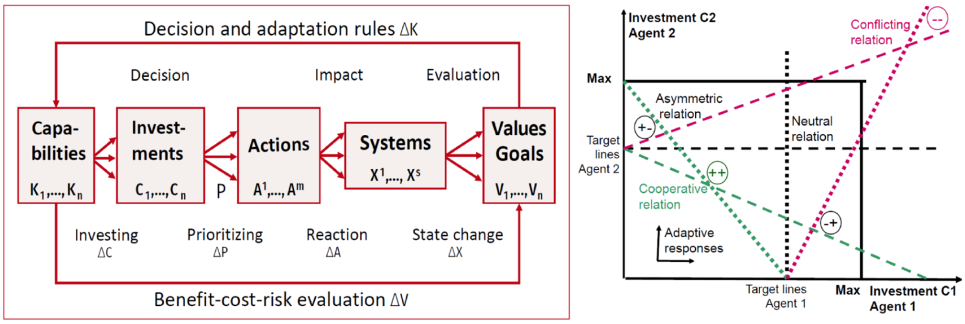

Figure 2: (a) Dynamic VIABLE model framework for multiple agents; (b) Adaptive target lines for two agents and mutual equilibria (balance of investments) for conflicting (--), cooperative (++), mixed (+-/-+) and neutral relations.

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4.4 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 we shortly refer to (Guo et al., 2023):

- *Causal learning* to identify multiple climate-conflict pathways and mechanisms based on large-scale data globally (Ge et al., 2022) and regionally (Xie et al., 2022). Recent work (e.g., in social transformation) integrates bifurcation behaviour with neural networks to harmonize data driven prediction with expert-informed climate fragility indices (Sun et al., 2022).
- *Statistical Mechanics* such as excitation-cooling models represent specific violent conflict processes, where a successful attack leads to more attempts while excitation can be cooled down by security forces increasing preventions which can be perceived as a tipping process (Tench et al., 2016). Case studies covered data from Northern Ireland, Iraq, and Afghanistan.
- *Diffusion processes* of spreading influence are particularly suitable for modeling large-scale expansive conflicts across conflict regions, such as Mali, Iraq or Afghanistan (Zammit-Mangion et al., 2012). Driven by geographical attractors, conflict can tip in one or another direction, represented by a dynamic diffusion map with abrupt tipping behaviours.

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5. Modeling tipping cascades in conflict and cooperation

5.1 Bi-stable tipping models in action

As suggested in Sect. 4, logistic and bi-stable models are applicable to tipping processes in human conflict and cooperation, for instance in animal ecology, where environmental factors such as food supply and temperature modulate whether insects fight or cooperate (Pruitt et al., 2018). In urban conflict models quantitative and qualitative factors contribute to the tipping process when a group of people take a new trajectory towards violent mechanisms (Moser and Horn, 2011; Beall et al., 2010). This can be influenced by conventional factors (socio-demographic, ethnic/religious/caste, crime categories, legal framework); short-term tipping triggers (economic, political and media events); and long-term tipping bias (unemployment, parental guidance, substance use, etc.). For instance, urban violence is studied for several case studies such as the gender-based violence in Santiago and political violence in Nairobi (2008), factional violence in Dili (2006) and Sudan (2011), and Patna riots to improve security in the city. Such bi-stable models are used below as part of a larger networked model to reflect global connectivity (Aquino et al., 2019).

Bi-stable models are visualised here by landscapes of potential functions ("energy") in which objects are driven by internal and external forces. They are one way to conceptualize tipping between conflict and cooperation as two stable states, whereby switching between them needs a certain amount of "extra" energy or incentive. We can 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): has independent variables that contribute to a probability of flipping between conflict and cooperation states, where the discrete model may not capture the tension and sliding dynamics.
2. *Continuous attractor model* (e.g., Potts, Kuramoto) with certain state(s) and independent variables that 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 or logistic map) has two stable states and entropy wells (or basins of attraction), that entrap an agent within it.

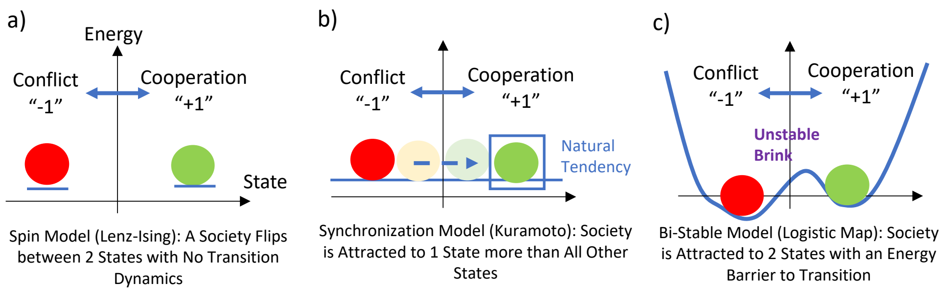

Figure 3: Concepts in modeling state transitions: (a) flip models, (b) attractor models, and (c) bi-stable models.

The third kind of tipping model is used to model the choice between cooperation or conflict under different environmental conditions. To create the simplest model that exhibits bi-stable tipping dynamics, we employ a third order polynomial for the rate of change of state x, where the unstable brink is a tipping point:

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

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 x, attracted towards the equilibrium state of cooperation C and a smaller conflict term K. An external forcing term F can include many factors such as trade, political influence, online influence, and climate change. In the following, we explore some critical states in the model (as shown in Fig. 4):

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- *Growth:* the greater the current level of cooperation x, the more cooperation occurs, subject to the 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 decline 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.

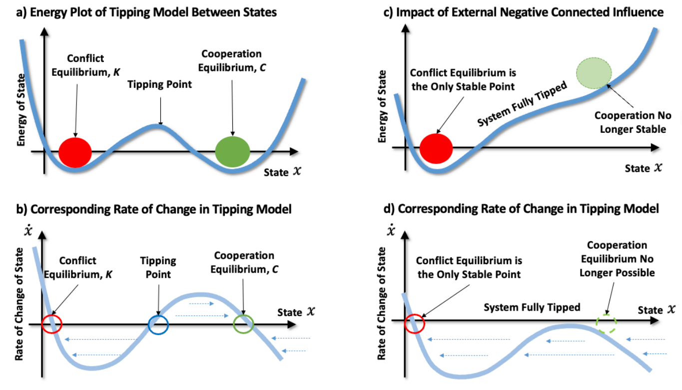

Figure 4: Transition between stable states via tipping point: (a, c) energy plot of tipping model under different circumstances of no tipping and fully tipped, and (b, d) corresponding rate of state change diagram.

The direction of growth towards cooperation (C) or decline towards conflict (K) is indicated by the light arrows pointing towards or away from these states. Fig 4a-b shows the corresponding energy and rate of state change plots for a standard tipping model. Fig. 4c-d shows the corresponding energy and rate of state change plots for a heavily tipped model to conflict.

5.2 Networked tipping cascades and self-enforcing dynamics in conflict and cooperation

State transitions between conflict and cooperation can occur when sufficient energy drives the process. In Fig. 3c, we showed the equation of bi-stable systems, and the state transition between stable states via the tipping point (unstable brink in between). In Fig. 4c-d, we see that when a system is fully tipped due to internal behaviour, external forces or other reasons, stable cooperation states can disappear, and the only stable point is conflict. Indeed, whether systems decide to be cooperative or in conflict can depend on many factors, which gives rise to "ambiguity" in literature where even fragile states can decide to cooperate or not depending on external support. As such, we are motivated to build a network of bi-stable systems to use the graph links to represent relationships between social systems (e.g., cities or countries).

Deleted: 5.2.1 Stable state transition scenarios

One way to capture diverse external forces between different nodes is to construct a multi-layer graph (Fig. 5) with:

- *Nodes*: Cities or countries.
- *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.

We create a multi-layered graph (Fig. 5a) with N settlements and the connected tipping dynamics for node i according to:

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

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 (Fig. 5b), as demonstrated in the Global Urban Analytics for Resilient Defence (GUARD) project (Aquino et al., 2019) where 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. Here, conflict data $x(t)$ at time t per node are used to fit with independent variables: previous historical state of $x(t-1)$ and the weight of graph connections to the node as independent parameters. Equation (2) describes the nonlinear relationship for change of state x, as well as the graph connections with other nodes via the multi-layer land transport connection matrix A, with friendly ties based on existence of economic or political treaties or military exchange/trade (1 or 0), and cultural similarity based on a religious belief vector of major religions (distance between vectors). The independent parameters are weighted by the $g(.)$ function determined by multi-variate regression. The data are from 2001 to 2017, and the conflict data (x) are from the Global Terrorism Database (GTD), where trade and transport data are from different UN, CIA, and National Geographic databases.

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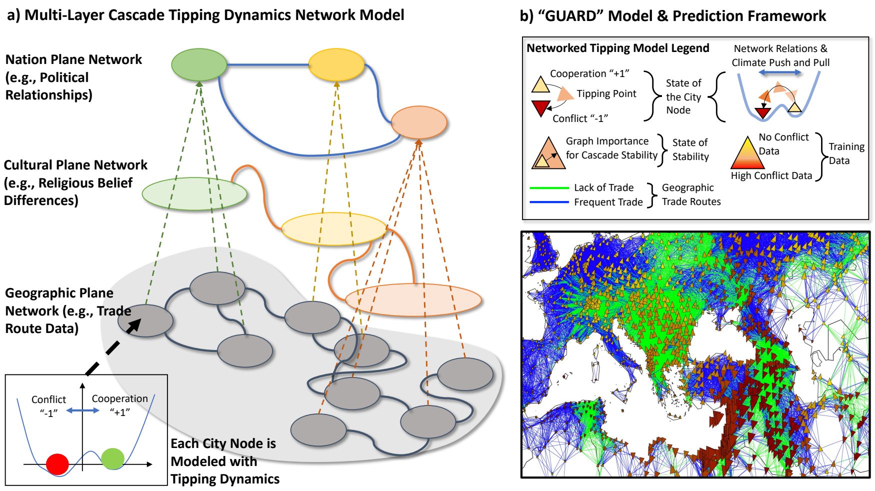

Figure 5: (a) Multi-layered graphs that connect local nodes (city) tipping dynamics with inter-city relationships across geographic, cultural, and national/political relationship layers. (b) Example results taken from the UK Alan Turing Institute GUARD project (Aquino et al., 2019). Legend: each node (city) can tip between cooperation (triangle point upwards) or conflict (point downwards). The size of the triangle indicates network cascade vulnerability, and the colour indicates validation data (red is conflict, yellow is lack of conflict data). The link colours represent multi-layer data, where blue indicates some evidence of positive cooperation and green is the absence of evidence of trade and friendly relationships.

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To analyze a networked dynamical system, various techniques can be applied, such as synchronization of nodes, states and links, stability of perturbations, uncertainty and robustness, as well as stochastic resonance of micro-oscillations and state transition. The technical challenge is the high-dimensional nature of the problem and the different dynamic perturbation combinations. One question is how increased negative perturbations on links can pull the system towards less cooperation states and more conflict, eventually a collapse to large-scale conflict and a loss of resilience (Moutsinas & Guo, 2020).

6. Regional case study for tipping cascades in conflict and cooperation

Following the climate-security discussion in Sect. 3, the review of tipping models in conflict and cooperation in Sect. 4 and the analysis of the transition dynamics in the bi-stable tipping model of Sect. 5, we now illustrate the conceptions and models for a regional example of a climate security hot spot familiar to many researchers, centred around the Lake Chad region. Translating qualitative narratives to quantitative networked tipping models introduced in Sect. 5, we show how different governance approaches (e.g., support vs. competition) and migration patterns can lead to an erosion or raising of barriers in conflict-cooperation transitions. The purpose is to show how narratives can map to models and not to develop a detailed or generalised Lake Chad climate-conflict scenario which is left to future research, e.g. implementing the VIABLE model.

6.1 Case study: the Lake Chad region

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). Over recent decades, Lake Chad has been facing strong variability in lake water levels and water flows from rivers, rapidly rising temperatures, longer dry seasons, heat waves, and sand/dust storms, have contributed to crop failures, livestock losses, and depletion of fisheries, and placed the region on the edge of systemic criticality and conflict tipping pathways. At the same time, the region has been afflicted by several political, identity, ethnic, communal, and resource conflict events, some of which 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 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 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 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 that 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.

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5.2.3 Cascading and self-enforcing dynamics in cooperation¶
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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 when triggered population displacements and complex emergencies in the region leads 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 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.

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An example of change in behaviour that is hard to reverse is the motivation amongst young people to embrace extremism (fuelled by abrupt breakdown in livelihood services). By generating income through participation in regional conflict economies, young people have now built capacity to defend rebel groups, seeking opportunities to perpetuate violence . This is made worse by the climate crisis and has become more widespread despite recent rebound in the Lake waters (Pham-Duc et al., 2020), raising doubt about claims that Lake Chad is shrinking and that this is due to climate change. Selby and Daoust (2022) find the policy discourse on conflict and security implications of climate change overstated, misleading, and out of line with scientific evidence. Gradual variations of water level have added a new twist: communities that moved and built homes towards the dry and small Lake Chad during the droughts of 1980s and 1990s are now having to confront massive flooding (particularly during rainy seasons and when the Lake overstretches its banks); many have lost their natural and physical assets (land, farms and houses) as the Lake expands, rebounds and recovers (the Lake is somehow reclaiming back the land areas it initially lost). We conclude that several mechanisms of the tipping point definition (self-perpetuation, substantial, widespread, often abrupt and irreversible impacts) can be found in Lake Chad region which combine in vicious circles between violent conflict and environmental degradation, including breakdown of livelihoods, oscillations of Lake Chad water, chains of violence and displacement, and rebel-controlled conflict economy, without one single cause (Newmann et al., 2023).

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6.2 Bi-stable tipping model in Lake Chad region

Based on the bi-stable model introduced in Sect. 5 we now demonstrate how it can be hypothetically applied to meso-scale communities in the Lake Chad region. In particular, we wish to show how the model can explain diverse and dynamic behaviours when under common climate stressors. Fig. 6 is a pictorial narrative on a multi-scale understanding of social communities and cascade tipping dynamics through interaction networks that either reinforce or compete with each other.

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In Fig. 6a, we show how a broad region (macroscale) contains two smaller scales of social interaction: (I) mesoscale communities that represent regions/tribes, and (II) disaggregated microscale individual entities (e.g., towns). Each microscale entity can be modelled by the previously described bi-stable tipping model in Sect. 5, whereby 2 stable states exist (cooperation and conflict). The barrier that exists between these states represent the societal "resilience" to change.

- In example Fig. 6a-i (blue community), we can see that a fragile social entity (internal parameter) can slide between conflict and cooperation without much incentive.
- In example Fig. 6a-ii (yellow community), we can see that long-term adversarial conditioning such as climate stressors (external forcing) can tip the scale away from cooperation towards conflict.
- In example Fig. 6a-iii, we can see that inter-group dynamics (alliances, trade, animosity) can push or pull the state of cooperation and conflict. Sometimes this can rest on an unstable "brink".

In Fig. 6b we can see an example of a community in the Lake Chad region, whereby it first experiences drought which seems to drive the social system to tip towards conflict (Fig. 6a-ii case), but this may not be enough. The first enabling pathway (Pathway 1) towards conflict is the migration of fishing communities away from its previous settlements – creating a power vacuum, which decreases the social resilience to change barrier (Fig. 6a-i case) and increases the opportunity for conflict actors to move in. This opens the second enabling pathway (Pathway 2), which is that the new 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 narrative of Lake Chad in Sect. 6.1, where more evidence of these pathways can be found.

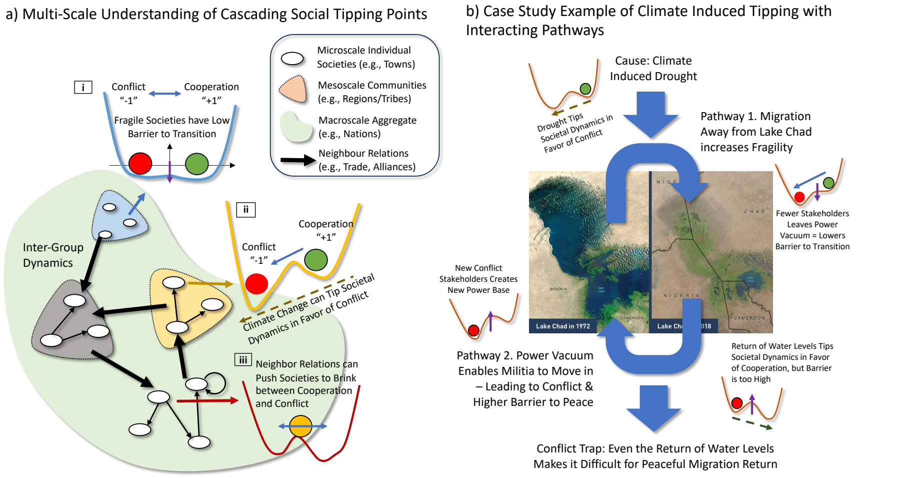

Figure 6 (a) Multi-scale understanding of cascading transitions between conflict and cooperation/peace, and (b) Example case study in Lake Chad region of climate induced tipping points with interacting pathways.

7. Governance challenges

7.1 Managing negative and positive tipping

Whether climate stress drives a system from undesirable to favourable pathways, from conflict to cooperation, or from vicious to virtuous circles, depends on the interaction of enabling and constraining conditions. Climate-induced conflicts require

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Deleted: see that a macroscale aggregate (e.g., nation, region), can comprise several meso-scale communities including individuals. Each community's behaviour and risk can be represented by the tipping model in Sect. 4 with two stable states (conflict and cooperation/peace). In these tipping dynamic systems, they are primarily affected by two variables:¶

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External forcing affects the tilt, biasing the likelihood of tipping one way over the other.¶
Here, we can see several cases (Fig. 6a): ¶
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.¶

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adaptive and anticipative governance (AAG) to effectively prevent and contain negative tipping and induce positive tipping towards cooperative solutions and synergies. To stabilize climate-society interaction under uncertainty and complexity, deeper understanding is essential about the underlying processes, how they interact and can be influenced. Besides data and experience, theories, models and scenarios contribute to tipping management and governance, including drivers and barriers of tipping points, their temporal and spatial windows and conditions for stability and controllability to prevent escalation. 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 tipping before it occurs and find preventive pathways to establish regulatory regimes and institutions when needed (Haasnoot et al., 2019; Juhola et al., 2022). To understand tipping cascades between climate conflict and cooperation, different techniques can be integrated, including system models, ABM, SNA and AI/ML to guide AAG actions. A stronger stakeholder engagement could benefit participative modeling interfaces. 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., 2022). Results can feed into institutional frameworks, such as the UN Climate Security Mechanism.

Besides predicting and avoiding negative tipping, governance opportunities for positive (desirable) tipping are essential, based on norms and goals to be achieved, such as the sustainable development goals, staying within the planetary boundaries, and 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 on 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 include scientific data and modeling as well as local and indigenous knowledge based on experience, mobilized in participatory approaches and collective learning.

7.2 Conflict transformation and environmental peacebuilding

While positive tipping cascades have been explored in fields of energy, food, transportation or finance (Eker et al., 2024), they are also potentially relevant in the transformation from cycles of violence to cycles of cooperation (Scheffran et al., 2014). Civil conflict transformation (CCT) uses only civil measures, such as mediation and conciliation, dialogue and diplomacy, violence prevention and peacebuilding. CCT can make an important contribution to prevent climate-related conflicts and support a sustainable and peaceful transformation, building a critical mass of agents with new attitudes, behaviours and norms.

One approach towards conflict transformation and cooperation is environmental peacebuilding, which focuses on managing renewable natural resources in conflict-affected areas, promoting sustainable peace through risk reduction and environmental collaboration, with spill-over effects for positive peace, human security and equity (Krampe et al., 2021, 2024). Examples on the regional scale are the EcoPeace Middle East project between Israel, Palestine and Jordan; collective rice production in Nepal; shrimp farming, mangrove fishery and flood protection in Bangladesh, among others (Schilling et al., 2017; Ide, 2019). On larger scales promising is North-South collaboration in decentralized renewable energy projects in rural areas of Africa or South Asia for economic development, local value chains, internet, mobile communication, education and health, better living

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Model scenarios can indicate tipping to conflict and how …to prevent and contain…escalation by political and legal measures… , 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. …oving 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 tipping disaster and conflict …efore they …t occurs and,…finding…preventive pathways for desirable change (e.g., Haasnoot et al., 2019). Conditions for 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 fa ... [43]

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conditions, jobs, and poverty reduction. 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. Emerging research sheds light on conflict-sensitive adaptation and maladaptation as well unintended and unanticipated consequences of environmental peacebuilding to strengthen positive legacies of peace (Ide, 2020; SIPRI, 2022; Simangan et al., 2023).

8 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. Following an introductory contexualization in complexity science and today's multiple crisis landscapes, a selective review and a structured overview (Sect. 2 and 3) highlight 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). The double exposure to conflict risk and environmental vulnerability compounds 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 Sect. 4. 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 behaviour 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 of complex multi-agent interaction in climate conflict and tipping cascades.

An illustrative bi-stable tipping model in action is presented and applied in Sect. 5, 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. Within the modeling context a regional hot spot perspective on the cascading "risk multiplier" role of climate change is presented in Sect. 6, using Lake Chad as a case study. Based on the bi-stable model we illustrate how in a macroscale aggregate of nations and regions, meso- and small-scale groups and communities can exhibit diverse and dynamic behaviours under climate stress between conflict and cooperation/peace. For poor governance community behaviour 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. Narratives that droughts can tip the social system towards conflict, need to be contextualized 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, Sect. 7 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 of the complex interactions contributes to forward-looking cooperative policies to prevent violent conflict and enable stabilization of the Earth system.

Competing interests: The contact author has declared that none of the authors has any competing interests.

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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 maladaptation (SIPRI, 2022).

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