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A framework for social tipping in climate change mitigation: What we can learn about social tipping dynamics from the chlorofluorocarbons phase-out

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ABSTRACT

In the natural sciences, the concept of "(natural) tipping points" has become a hot topic in climate change research. To better understand and evaluate the possibilities for and the barriers to the fundamental societal transformations necessary for climate change mitigation, we suggest a *social tipping dynamics* framework. We contrast this framework with previous accounts of stability and change and show that integrating these approaches under the umbrella of a *social tipping dynamics framework* provides us with a more encompassing and therefore more realistic account for theorizing and empirically analyzing the different (technological, behavioral, and political) paths and related interdependencies to fundamental societal change. Moreover, by emphasizing the *agency* aspect, we highlight that the type of fundamental change required in effective climate change mitigation is more strongly actor-driven than previous approaches have suggested. In a second step, we apply our framework to the phase-out of chlorofluorocarbons and thereby illustrate its merits. To conclude, we summarize the value of the concept of social tipping dynamics, including its limitations and potential for improving political analysis.

1. Introduction[1]

The concept of "(natural) tipping points" has become a hot topic in climate change research. The idea is that for a tipping element a small perturbation can suffice to irreversibly push a system into a qualitatively different mode of operation due to strongly self-amplifying feedback [1]. Several large-scale natural tipping elements have been identified in the climate system [2-5]. For example, in the decay of the West Antarctic Ice Sheet (WAIS), after a certain local temperature point has been crossed, it would be hardly possible to stop its degradation, leading to a qualitatively new situation [6]. This predicament renders political action and international agreements, such as the Paris Agreement, [7] indispensable steps in stopping or at least decelerating the tipping of the climate system.

Recently, a growing body of literature has (re)discovered the usefulness of the concept of *tipping* for the social context, and in particular regarding climate change action e.g., [8–12]. These studies introduce the idea that effective climate change mitigation, i.e., activities that prevent or at least delay natural tipping, requires fundamental societal transformation,[2] that is, a *social* tipping, e.g., a change from a previously high level of CO_2 emissions to a new zero-CO_2 emissions state [10,13-16]. Moreover, while in contrast to natural tipping, social tipping is seldom completely irreversible, it still brings the system into a new stable state. According to the definitions by Milkoreit et al. [10] and Otto

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[2] We use the notions "climate change mitigation," "climate change action," "sustainability transformation," and "decarbonization" interchangeably to describe activities that may prevent or at least delay the natural tipping triggered by anthropogenic climate change.

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et al. [11], for instance, these fundamental and non-linear societal changes can be triggered by rather small causes, whereas their outcomes might seriously affect the socio-ecological Earth System. We align with this strand of research in arguing that the social tipping approach can fill a gap in the theoretical landscape with respect to conceptualizing and understanding a specific type of change, namely, change that is fundamental and drastic as well as encompassing, i.e., involving the political, technological, and behavioral spheres, and hence, the type of change that is needed for climate change mitigation see also [17]. We also go further than previous studies in two respects.

First, in order to make the advantages of the social tipping concept explicit we discuss previous theoretical accounts of "change." We argue that, in view of the kind of encompassing change necessary for sustainability transformation [10,13,18], these previous approaches all have their strengths but also their shortcomings. We reason that a social tipping approach combines the strengths of previous approaches as it accounts for radical shifts leading to new states of stability, but also highlights and makes more explicit the role of political and societal actors [19], including so far neglected aspects, such as public opinion [20], as well as individual preferences and behaviors [12,21-23]. We are not the first to emphasize that the rapid and fundamental change in parameters, such as CO_2 emissions, biodiversity preservation, reduction of waste, and so on, are not just about physics or technology but have political and behavioral tipping dimensions [24,25], which are often triggered and driven by rather lengthy processes [26]. However, by emphasizing the *agency* aspect, our framework highlights that the type of fundamental change required for effective climate change mitigation is more strongly actor-driven than previous approaches have suggested.

Second, the social tipping approach can only tap its potential if it is translated into a consistent conceptual framework. We therefore propose such a conceptual framework, which – besides its afore mentioned focus on agency – integrates two further elements we consider crucial to make tipping a fruitful concept in the social and political science context. On the one hand, we use and develop the notion of social tipping *dynamics* rather than social tipping *points*. We argue that the former is a more realistic account to capture the nature of *social* tipping, since we consider social tipping, in some sense, to be more complex than a natural tipping point as it is more likely to be influenced by agency, a multitude of social-institutional and cultural networks, and different spatial and temporal scales [11,18,24]. By contrast, natural tipping points are often understood in terms of one control parameter, e.g., global mean surface temperature, crossing a critical threshold [3]. On the other hand, we argue that social tipping dynamics describe processes consisting of three key sub-dynamics, namely the technological, political, and behavioral, as well as their interlinkages. These sub-dynamics can by themselves, but most likely in combination [see also [26], tip a system from one qualitative state to another.

The main goal of this article is to make the case for a framework of social tipping dynamics in the discussion of mitigating anthropogenic climate change. Our central argument is that a holistic view on integrating change in the technological, political, and behavioral spheres, while making the actor-dimension more explicit, is needed to conceptualize and better understand the type of fundamental change required in climate action to reach the Paris goals. Our contribution is a step towards empirical applications of the social tipping approach by identifying the spheres in which such tipping processes may be particularly relevant, by integrating previous approaches to theorize the different paths, and by illustrating the empirical potential of a social tipping dynamics framework.

Our paper contributes to an ongoing discussion about how perceptions from socio-technical transition studies can be combined with insights from the political and social sciences, for example by considering how interest groups form coalitions to bring about or obstruct change and how policy feedback and political context matter for technical transitions [19,24,27]. Put simply, while previous accounts on social tipping and societal transformations have identified the political sphere as an important aspect of fundamental change, we strengthen and specify the political dimension in our analysis of tipping to better understand how, where, and under which conditions it enables or hinders the type of change necessary for effective climate change mitigation. The practical relevance is obvious, especially since low carbon transition is "being actively pushed by policymakers on an international level, in a way unlike any other energy transition on historical record" [19], while little has happened at the level of its implementation.

We start our paper with a brief presentation of how social tipping has been conceptualized in previous research. Then we present our holistic social tipping dynamics framework, which identifies the three sub-dynamics that each on its own—but most likely in conjunction—can trigger social tipping, and which theoretically integrates different explanations and mechanisms to explain change or the absence thereof. Next, we empirically illustrate the added value of our framework by applying it to a case previously thoroughly analyzed in the scholarly literature [28,29], the phase-out of chlorofluorocarbons (CFCs). We conclude with an outlook and a discussion of potential paths for future research.

2. Social tipping

An emerging body of literature has emphasized the need for fast and encompassing societal change, i.e., *social* tipping, to bring about the necessary changes to meet the goals of the Paris Agreement and to stop or at least decelerate the tipping of the climate system cf. [10,11,15,24]. While the notion "tipping point" has been used in the social sciences before, when Schelling [31] prominently employed it to discuss neighborhood segregation, it was re-introduced to this field and, more precisely, to the discussion on climate change mitigation only in the late 2000s [1,31]. Since then, many different propositions have been made on how to conceptualize and identify social tipping. In a recent literature review, Milkoreit et al. [10] conclude that this diversity currently limits the scholarly utility of the tipping approach. We take this claim as a starting point to present a framework that can enable researchers to use the concept not only in a metaphorical sense [[10], p. 2] but also in an analytical way. In so doing, we first outline the common grounds of the previous literature to show how well they can be integrated in a social tipping framework, as well as the ways in which a social tipping framework transcends these previous approaches.

According to Milkoreit et al. [10], some core elements are repeatedly used in many social tipping definitions and can thus be understood as central aspects of the social tipping concept. Social tipping relates to the existence of multiple stable states between which systems can tip, implying that once a new stable state is achieved, it is impossible to go back to the previous state. Tipping happens when the system is in a critical state [[18], p. 1]: here, a small perturbation can suffice to push a system into a qualitatively different mode of operation due to strongly self-amplifying (mathematically) positive feedback [1]. Moreover, social tipping is abrupt, to a certain extent unpredictable, and involves a considerable magnitude of change. Many authors understand social tipping dynamics as the spreading processes of norms, opinions, behaviors, and actions through complex social networks that are irreversible and difficult to stop [11,12]. In addition, Farmer et al. [[13], p. 132] identified sensitive intervention points (SIPs) in which "an intervention kicks or shifts the system so that the initial change is amplified by feedback effects that deliver outsized impact." In these instances, systems shift trajectories, either with or without changes in the underlying system dynamics (e.g., the rules of the game).

These characterizations of social tipping closely follow the discussion about natural tipping points. However, little is yet known about whether natural and social tipping display the same underlying mechanisms [[10], p. 2]. Nevertheless, previous research depicts at least two relevant differences between social and natural tipping.

First, and in contrast to natural tipping, which, in the context of global warming, is most often an unwanted process, social tipping can

involve both desirable and undesirable dynamics [18]. Recent studies focus on positive social tipping [26], namely "emergent properties derived from complex systems dynamics that allow rapid transformations in individual and collective practices so as to reach evolutionary-like solutions to the present socio-climate quandary" [[15], p. 120]. We align with this perspective and focus on (normatively) positive tipping towards effective climate change mitigation, i.e., emphasizing the need within the social and political sciences to better explain and understand the rapid and fundamental change necessary to stay within the planetary boundaries [33].

Second, both Trutnevyte et al. [17] and Farmer et al. [13] point to the fact that tipping in socio-ecological systems depends on a number of different processes and dynamics. Trutnevyte et al. [17], for instance, call for integrating the social sciences (e.g., behavior of different actors, transformation dynamics in time, and heterogeneity across and within societies) into established models that often focus on technology, the economy, or policy. This corresponds to the view that social tipping will always strongly depend on and be triggered by actors and their behaviors, their networks, and the agency (see section 4.3) vested in them, with the latter being "central to implementing transformations needed to limit global warming and achieving the SDGs" [[14], p. 7].

Against the background of this previous research and given our theoretical focus on how to explain the change necessary for effective climate change mitigation, we therefore define social tipping as a *fundamental and accelerated change (a rapid societal transformation), in which societies go from one technology or social practice to another in a short period of time*. Where tipping occurs, this typically reflects or can be illustrated by curves, in which an outcome indicator, e.g., CO_2 or CFC emissions, exhibits a sharp increase or decrease after longer periods of (steady) increase.[3]

3. A social tipping dynamics framework

In this section, we propose a social tipping dynamics framework that aims to bring the social tipping concept one step closer towards empirical application. Previous research documents that social tipping is particularly suited to conceptualize that particular type of fundamental change needed for effective climate change mitigation. However, as we argue, to make the social tipping approach useful for empirical applications, we need to transform it into a conceptual framework that helps to theorize and identify the mechanisms leading to social tipping. Our conceptual framework thus facilitates the identification of relevant research questions as well as the factors and processes that need to be considered when analyzing the profound political, technological, and behavioral changes necessary to mitigate climate change.

3.1. Why we need another framework

Why do we need yet another approach when there are already several well-established approaches intended to explain political change, or rather the absence thereof? We argue that although previous approaches provide helpful arguments and mechanisms to explain specific aspects and types of change, they either fail to explain the specific type of transformational system change required for sustainability transformation or to incorporate the key societal dynamics that are likely included in tipping processes. We propose a holistic framework that brings the strengths of previous theoretical accounts together in order to better explain and understand the specific type of change in which we are interested, namely where a small change or 'kick' can have a huge outcome through positive internal feedback processes [[11], Table 1].

Our framework is characterized by three crucial elements: a) a focus on social tipping *dynamics*, b) the inclusion of three sub-dynamics that alone or in combination might trigger tipping processes, and c) an emphasis on the role of agency in social tipping. In the following, we explain these elements in more detail and set out how they speak to or integrate previous accounts of change.

a) A focus on social tipping dynamics

In some sense, we understand social tipping dynamics as more complex than natural tipping points. To illustrate the tipping idea, Kopp et al. [9] present the example of a rail coal wagon as the tipping element that falls to its side (is tipped) due to overload. An example to illustrate this idea of tipping in a political context could be a country that is part of an international committee that, by switching from being an opponent to a supporter of a specific measure, changes the political majority within this committee in favor of that measure. However, the kind of social tipping necessary for effective climate change mitigation is more complex than that and, in contrast to natural tipping points, includes different actors and spheres, along with different spatial and temporal scales, as well as their interactions [18,24]. Social tipping does not strictly follow physical laws as do natural tipping points but has a political and behavioral dimension, which makes the process more volatile and more difficult to predict. Moreover, political and societal systems are complex networks that connect numerous individual and collective actors from different areas (e.g., politics, society, economy, technology, and science), who are vested with different degrees of power and sets of preferences on multiple levels of the state, from the local to the national and supranational [14]. Complex contagion approaches show how "the spreading of an action, behavior or trait through a complex network" can "foster social tipping" [[12], p. 1]. It is thus neither possible to identify a single parameter or mechanism, i.e., the relevant "piece of coal," that instigates social tipping events, nor does a specific change in or to a system deterministically result in similar effects across space and time. Overall, even if a critical juncture affects future paths [34], social phenomena or processes can be stopped, and new trajectories can become a reality due to agency and networked processes. Therefore, we argue that the idea of "social tipping dynamics" more realistically accounts for these complexities.

b) Three sub-dynamics

The political and public discourse on sustainability often centers around decarbonization and the technological advances necessary to reach the zero-emission goal. From the literature on technological transitions, it can, however, be concluded that rapid and fundamental transitions involve not only the technological sphere but also the social context in which technological innovations occur, i.e., the socio-technological landscape [24,35]. We follow this line of reasoning by arguing that to better understand these dynamics, we need an even more nuanced view that goes beyond technological innovation. New technologies are central to achieving the goal of rapid global decarbonization. Yet, it is the political rules and regulations that define the playing field, as well as other factors, such as subsidies and public funds that enable research and development [28]. Moreover, individual consumer choices are relevant for a product's success, and citizens' decisions are (directly or indirectly) relevant to defining the political context in which the change occurs. Building on the key findings of political science research, we thus distinguish between two additional tipping sub-dynamics, namely, the *political* and *behavioral,* besides the *technological* sphere. The political dynamic concerns changes arising from the political decision-making process, e.g., in political majorities

[3] With this definition, we place ourselves within the current social tipping literature, while another prominent concept to describe the specific encompassing societal change is that of transformation or transition. This literature is divided about what exactly is being transformed, and why and how [24], but some definitions see features relating to the non-linearity or the fundamental nature of change as central aspects. In this vein, our conceptualization of social tipping may be understood as a specific type of societal transformation.

and, relatedly, in government policies. The behavioral sphere captures changes in how individuals and social groups react to the challenges of climate change mitigation, i.e., in terms of their everyday behavior but also regarding what they demand from the technological or political sphere.

Hence, in our framework, we argue that social tipping dynamics describe processes consisting of the three key sub-dynamics—technological, political, and behavioral—as well as their interlinkages (see Fig. 1). These sub-dynamics can by themselves, but most likely in combination, tip a system from one state to the other [see also [26] or [24]]. A framework integrating these different spheres acknowledges that processes of change may be most fundamental and sustainable if they are triggered simultaneously or interrelatedly from different angles [25]. In this direction, we build on Trutnevyte et al. [17] and Farmer et al. [[13], p. 134], who reason that there is "a strong coupling among these different domains, which makes models built within silos unable to provide the guidance needed." More precisely, we aim to illustrate the potential of technological, political, and behavioral dynamics to tip a system into a qualitatively new state. In fact, and this is one of our core arguments, it is rather unlikely that one alone will lead to large scale social tipping, which is illustrated by the overlap of the three dynamics in Fig. 1.

Moreover, due to the particular mix of individual, regional, and national interests involving numerous actors (i.e., institutions, interest organizations, parties) on different (state) levels, social tipping dynamics can be influenced by various factors. These are visualized in Fig. 1 as ideas, material conditions, and/or external shocks that can—channeled through institutions and interests—act as triggers of change. Our focus is to understand the social tipping dynamics these factors trigger.

Distinguishing three spheres in which change happens, including their interaction, borrows from earlier approaches but also differs from them in important ways. Beddoe et al. [25] emphasize that system change towards sustainable societies needs to involve different spheres, i.e., worldviews, institutions, and technologies. However, we argue that their conceptualization of this change as "evolutions" (whereby cultural evolution triggers new institutions and technology) does not capture the (actor-induced) dynamics we should focus on, namely, how and why these changes are actively triggered (see [36]). O'Brian and Sygna [24], with their distinction of a practical, political, and personal sphere of transformation, do indeed emphasize the actor dimension more strongly, yet they do so mostly on an individual, socio-psychological level rather than on a political level. However, while they see these spheres as strictly ordered, with the practical sphere as the "outcome" at the core, and all three spheres necessarily involved in fundamental transformations, our three spheres are non-hierarchical, and they do not include but lead to the "outcome", i.e., social tipping. The overlap in Fig. 1 emphasizes that processes in all three spheres have an equal potential to trigger the type of fundamental change we are interested in. In addition, Fig. 1 illustrates that we should not neglect the possibility that one sphere alone can lead to social tipping, which sets us apart from the previous literature.

Intentionally, our framework does not include a time component, as we imply neither that the described processes are linear nor that there is a fixed sequence of events necessary to tip a system. Furthermore, while tipping as such is rapid, the processes leading up to tipping can be very lengthy or quite sudden [18]. Nevertheless, we assume that the more interlinkages we observe between the sub-dynamics, the more likely we are to see changes towards the system being tipped, which is represented by the darker interlaps in Fig. 1.

c) The role of agency

Our framework is actor-centered, as we believe that a framework on social tipping dynamics should emphasize the role of agency in a networked structure. Agency can be understood as the human capability to, on an individual or group level, not only make decisions and implement them but also to take potential consequences into account and thus to actively influence future outcomes [37]. In the Anthropocene, this human ability to influence the future through deliberative individual and collective action, and to form networks, is understood as being crucial for sustainability [14].

Agency is particularly relevant in the political and behavioral tipping sub-dynamics. Most obviously, political change is a consequence of actors making or influencing political decisions (e.g., through voting, lobbying, social movements, opinion formation, and opinion change). Also, at the individual level, a technology by itself does not change the world unless it is actually accepted and used by consumers. Furthermore, individual values, risk assessments, and concerns, as well as the willingness and capacity to change behaviors, are crucial factors to mitigate anthropogenic climate change [38]. Social tipping is thus intentional [26], while natural tipping is not. However, this does not imply that actors' intentions are always (directly) aimed at social tipping and cannot have unintended consequences.

Moreover, actors add complexity to the way processes of change evolve. First, actors' preferences rarely are homogeneous. Instead, it is likely that they are as heterogeneous as are members of Parliament, who represent different parties with different programs, as well as their constituencies with their own characteristics (e.g., demographics, economic structure). The same holds for other actors involved in the political decision-making process, e.g. parties, interest organizations, institutions, and also citizens. The question of when or how a social system tips[4] is thus crucially related to learning more about when and how a majority of these heterogeneous actors "moves," e.g., by asking for policy change, adopting new ideas or strategies [36]. Accordingly, the interlinkages and dynamics between these actors need to be considered.[5] For instance, being the first player to move (i.e., adapt a new strategy) can be perceived as costly, but as actors have heterogeneous cost functions, first mover action can be crucial. When the first actor moves, the utility functions for other actors change, which can trigger more actors to follow [39].

The main benefit of the social tipping dynamics approach is that it explicitly focuses on radical and rapid changes leading to a qualitatively new state (i.e., changing paradigm), while at the same time, it goes beyond the scope of transition studies, emphasizing that such radical shifts can be triggered not just by the technological level or system characteristics—though this still has importance—but often are the result of specific actors' behavior across different spheres. This actor dimension comprises both dynamics at the citizen level (changing norms and behaviors) and at the level of the political elite who trigger policy change.

3.2. Integrating previous theoretical accounts on change

While the relevance of our framework lies in its holistic perspective, it also emphasizes that previous theoretical accounts of behavioral, political, and technological change need to be integrated to theorize the different sub-dynamics and, thus, the paths to tipping.

In the following, we illustrate this by discussing several prominent approaches from the social and political sciences that provide important arguments and mechanisms under which change does or does not happen. We show how these approaches can be used to theorize different aspects of the three sub-dynamics and why we need to combine their strengths to get the "full picture" of social tipping dynamics.

[4] For an overview of the potential early warning signals of critical transitions, refer to [83].

[5] See Wiedermann et al. [12] for a network-based microfoundation of Granovetter's threshold model for social tipping.

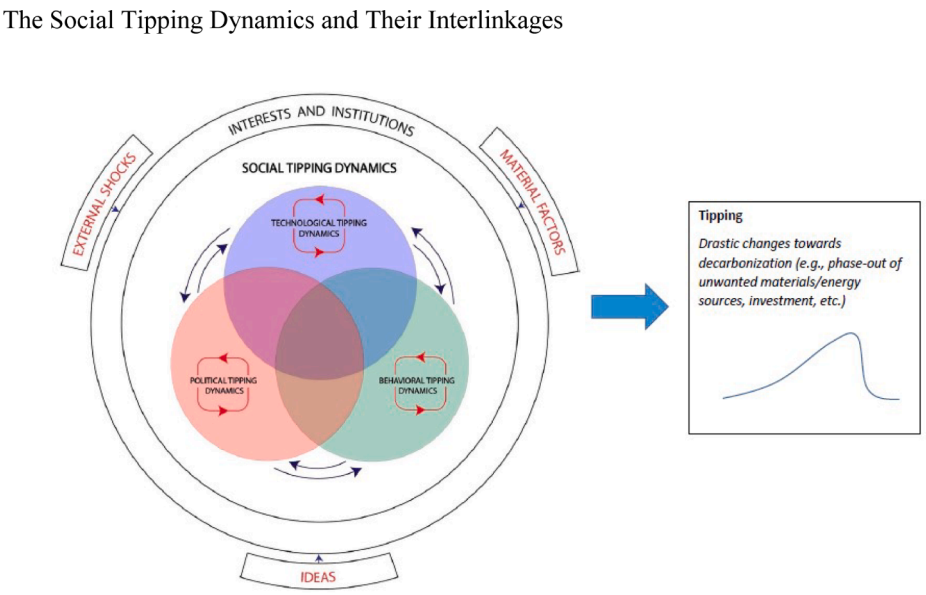

Fig. 1. The Social Tipping Dynamics and Their Interlinkages *Source:* Own illustration.

a) The technological sub-dynamic

In recent research on technological change, it has been common to focus on so-called socio-technological systems, emphasizing how societal change and technological transition interact. More specifically, research on "sustainability transitions" [40] builds on the observation that the widespread diffusion of sustainable technological innovations is low and investigates how radical innovations emerge, are able to overcome resistance by incumbent interests, and eventually lead to major system changes [35].

Whereas the existing socio-technological system is defined by stability and lock-ins due to factors such as sunk investments and institutional commitments, niche innovations describe the introduction of new technologies that either succeed or fail. When there is a window of opportunity that is formed by the socio-technological landscape moving (in our case, some form of behavioral or political change), and new technologies have gained momentum, a change of the existing socio-technological system is possible [26,39,40]. Recently, the role of technology decline has been emphasized [e.g., [40]]. An important point is that several innovations are typically needed to bring about a change in the energy system. Geels et al. [[43], p. 1242] exemplify this argument by the extraction of shale gas, which came about "when seismic imaging, horizontal drilling, and hydraulic fracturing were combined."

This strand of research aims at explaining fast technological change. However, its strong focus on technology risks neglecting the important role of agency and, more generally, the political, economic, and societal spheres [19]. Indeed, most previous studies have "focused on the immediate technological and economic drivers of acceleration" [[44], p. 1]. It is argued that the socio-technological landscape is the broader context that influences socio-technological regimes, while actors have little or no influence on that landscape [[27], p. 225]. However, we expect that political intervention is crucial to steer actors' behavior on a sustainable trajectory and help actors coordinate their actions in large-scale collective action imperatives, such as climate protection [cf., [43]]. Hence, to understand fundamental and accelerated change, research needs to incorporate the political sphere and individual-level data on policy support and social norm change more strongly.[6]

b) The political sub-dynamic

This sub-dynamic captures fundamental and rapid change triggered by politics, and more specifically by government policies. Most obviously, a ban on unwanted practices or technologies can lead to a process whereby the use of a technology or the emission of a specific material is phased-out. Hence, the central question from the perspective of the political sub-dynamic is under which conditions do political majorities tip towards such policies?

Most previous political science approaches inform us about why such political tipping is difficult and rare. Most prominently, institutionalist approaches and related concepts, such as path dependency [46] and the veto player theory [47], provide compelling arguments for why institutions and policies are stable most of the time. Due to a process of self-reinforcement whereby "each step in the same direction makes it increasingly difficult to reverse course" [[48], p. 170], "policies persist unless there is a strong force exerted for change" [[49], p. 1282]. Especially political systems in which many actors or institutions have a say in policy making contain systematic barriers to rapid change [47].

Assuming a social tipping perspective, we thus need to focus on explanations for these rare cases where—despite this stabilizing nature of political systems—fundamental policy change is possible [50]. Theoretical approaches that provide such explanations are, for example, the advocacy coalition framework (ACF) [49,50], the epistemic communities framework [53,54], the multiple streams framework [53], and the punctuated equilibrium framework [56]. When targeting more systemic change, beyond policies, we might even consider broader approaches, such as theories of the causes of revolution [57]. Whereas all these approaches emphasize different aspects, they are partly complementary in identifying the relevant conditions and processes allowing for major change. Most importantly, they emphasize that external system events, such as changes in public opinion or governing coalitions, decisions taken by other subsystems, new scientific insights, or redefinitions of problems, can serve as game changers and lead to windows of opportunity or critical moments when fundamental policy change is possible [50].

Moreover, while not focusing on radical change, policy feedback approaches [58,59] provide potential mechanisms that can bring a system into a "critical state," from which it may tip to a qualitatively new state. This idea has been recently emphasized by, for example, transition scholars, who argue that in order to understand change in the

[6] For recent approaches to more strongly integrating the role of policies and the political discourse, see [19,38,42].

socio-technical landscape, as well as the potential for far-reaching change, it is necessary to understand policy feedback, i.e., how the introduction of a policy shapes preferences for future policies, and their role in technological transition [19]. Policy feedback, following Skocpol [[58], p. 58], refers to the many ways in which "policies, once enacted, restructure subsequent political processes." As Skocpol [58] points out, policies may transform structural factors, such as state capacities and administrative arrangements, but also the identities, goals, and capabilities of elite actors and citizens. Feedback implies some oscillation between policies and opinion, where change on the one side leads to a corresponding change on the other side, which is, however, different from the type of change in which we are interested. Nevertheless, in this context, Daugbjerg [60] suggests that policy feedback processes can lead to paradigm shifts when incremental reforms and related feedback dynamics change power structures and the perceived distributional effects of current policies so fundamentally (but often in an unintended way) that, eventually, more radical reforms are triggered. In this view, the idea of feedback may provide some arguments on the *conditions* that trigger tipping dynamics—for instance, if the consequences of climate change become visible and proximate [61] to the public inducing (important) normative shifts.

c) The behavioral sub-dynamic

While the political sphere is often understood as the macro level, individuals represent the micro level. As such, individuals can take different roles; for instance, they can be citizens, consumers, recipients, distributors of information, etc. As stated above, humans are vested with agency and thus the power and ability to act and actively influence the future [37].

Individuals do not act in isolation, however, but are connected to each other through (complex) networks consisting of family, friends, coworkers, membership in organizations, etc. Some individuals have more connections than others, some represent a more central node in a network, and some are more isolated; in short, some have more resources than others [62]. Schill et al. [22] therefore argue for putting individual behavior into context and understanding humans as "encultured" and "enearthed," that is, as socially and culturally embedded and part of the biosphere. According to the complex contagion phenomenon, these networks allow for the spreading of information, ideas, opinions, expectations, values, norms, and behaviors. The Granovetter model [63], for instance, was developed to explain how collective action emerges, and Wiederman et al. [12] build on this by demonstrating how even societal minorities can trigger social movements and crowd-like behaviors relevant to sustainability.

These mechanisms are particularly pertinent for democracies in which citizens are vested with considerable political power. Through the power of their vote, they are capable of changing governments and thus the political course of the country and beyond. On non-election days they also have ample opportunities to influence the decision-making process at all levels of state, either as individuals or through collective action [64]. In a dramatic example, what started off as a school boycott by one single girl in Sweden quickly developed into a global movement. In addition, public opinion plays an important role in the sense of the "public as a thermostat" [65]. Even in more autocratic regimes, people have the power to change the fate of the country, as was proven by the Monday demonstrations in the former German Democratic Republic, for instance.

Furthermore, individuals are consumers and, as such, have the potency to affect markets and companies. This so-called political consumerism [cf., [66]] assumes that some decisions to buy or not buy certain products are based on political as well as environmental reasons, a mechanism that is part of the so-called trading-up phenomenon (California effect) by which greener jurisdictions can trigger less environmentally strict jurisdictions to adjust their environmental regulations in order to serve the respective markets [67]. For example, if customers start shopping for regional and organic produce, supermarkets will adapt their selections. If demand for energy-saving appliances increases, companies will produce them. Similarly, individuals can change their behaviors towards more environmentally friendly options by, for instance, avoiding plastic packaging, starting to recycle, or switching to public transport for commuting. These changed behaviors might not seem like much on an individual level, but they might lead to large effects if others mimic them [12].

In general, the attitudes, norms, risk perceptions, and behaviors of individuals have the potential to tip societies towards more sustainability [68-70], but can also cause backlash, as the yellow vest protests in France showed [71]. However, these dynamics are more prone to change than technological developments or political decision-making, as attitudes and opinions can change quite quickly and individuals' very capacity to change has to be factored in. Also, tipping can either happen from the bottom up, when a critical mass of individuals gets activated [12], or from the top down through external activation, e.g., a new policy [28]. Consequently, albeit behavioral sub-dynamics might not be sufficient for social tipping, without fundamental individual change, sustainability will be next to impossible to reach.

3.3. The benefits of a social tipping framework

The above discussion illustrates that previous approaches to change provide helpful arguments and mechanisms that underline the importance of each of the three sub-dynamics to explain fundamental change. At the same time, however, the discussion also demonstrates the limitations of existing approaches to explain the profound transformations that are necessary to meet internationally defined climate targets. For example, transition studies offer good tools to explain radical shifts and changing paradigms on the technical side. However, they underestimate or fail to explicitly conceptualize the role of societal and political actors' behavior in influencing this change. Conversely, previous accounts on policy change can explain the absence of radical change and provide some insight into the special occasions when such paradigm shifts may happen in stable political systems. However, they remain rather vague in systematizing how to more specifically theorize "external system events" [72] that may trigger and even be necessary for radical change. Finally, approaches focusing on the attitudes and behaviors of individual and collective actors provide important insights into how mechanisms on the micro level can trigger or at least support tipping mechanisms. Yet, they sometimes neglect the broader context, e.g., the political sphere or culture in which an actor is nested.

We therefore argue that a framework on social tipping dynamics provides a powerful approach combining the strengths of the varying existing approaches and explicitly considering the interaction between the political, technological, and behavioral spheres [[13], p. 134, [17,24]]. In other words, our main claim is that we need to consider and analyze all three sub-dynamics to understand more profoundly when and under which conditions social tipping will or will not occur.

4. Applying the social tipping dynamics framework: the CFC ban as a case study

We employ the phasing out of chlorofluorocarbons (CFCs), a class of chemicals responsible for the depletion of the ozone layer, as a historical example to illustrate the merits and pitfalls of existing approaches and to highlight the added value of a social tipping explanation. We chose this example as it is often regarded as the prime example to illustrate "the human ability to internally interact with planetary geological forces" [[14], p. 7] and, as highlighted in Fig. 2, it shows the type of drastic and irreversible change we are talking about in this paper.

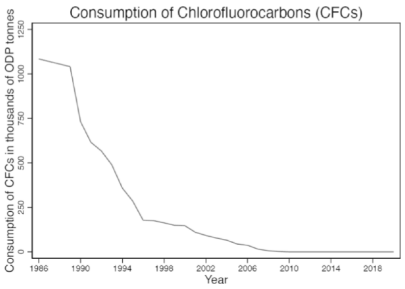

Fig. 2. Tipping in the Consumption of CFC *Notes:* Data on CFC consumption is taken from the UNEP Ozone Secretariat (https://ozone.unep.org/countries/data) and measured in thousand tonnes of Ozone Depleting Potential (ODP).

For a long time, CFCs were thought to be the "perfect chemical" [[73], p. 222]. As a non-flammable and non-toxic substance, they were used in refrigerators, fire extinguishers, and air conditioners. However, in the 1970s, science demonstrated the detrimental effects of CFCs on the ozone layer. This new scientific knowledge came as a shock to the existing system (see Fig. 1) and, as a consequence, several countries, such as Canada, Sweden, and the United States, unilaterally banned the use of CFCs in aerosols [73,74] in the late 1970s. Thus, and in response to the external shock of discovering and scientifically understanding the phenomenon of ozone depletion, *political tipping dynamics* (red circle in Fig. 1) regarding CFCs set in in various countries. While these domestic political dynamics in the front-runner states were an important first step, it became clear that unilateral action would not suffice and that international cooperation would be necessary [75]. Hence, these domestic political tipping dynamics were one trigger for international political change, i.e., the negotiation of the Montreal Protocol on Substances that Deplete the Ozone Layer.

However, such an account misses important additional steps in the process, which probably were even more important for the phasing out of CFCs. The unilateral policy changes in the U.S. of banning CFC aerosol products in 1978 [30] also triggered technological change and thus initiated *technological tipping dynamics*, which created the basis for a non-linear transformation in phasing-out CFCs (blue circle in Fig. 1). In the 1980s, new technologies, or rather replacement technologies, became available, which did not have the same detrimental consequences for the ozone layer. Once one of the main producers of CFCs, the U.S. company DuPont, was able to produce these substitutes, the company went from lobbying against banning CFCs to actually supporting their phasing out [29]. Since the production of CFCs was concentrated in very few companies for which CFCs were not the only, or major product, and which were located in very few industrialized countries, this created a feedback loop in the system, and implied a very favorable bargaining situation to reach stringent international standards, as happened with the negotiation of the Montreal Protocol and its successor protocols.

In addition, the example of phasing out CFCs also stresses the important fact that the different sub-dynamics or circles, as shown in Fig. 1, interact with and, in this case, reinforce each other. This is nicely illustrated by the fact that once DuPont was able to produce substitutes, the company intensively lobbied for international regulation in order to level the playing field in such a way that other producers could no longer make economic gains by producing CFCs [29]. This, in turn, reinforced the political tipping sub-dynamics, this time at the supranational level. The mechanism of relying on (inter)national regulations to force other market participants to comply with higher environmental standards, which is typically labeled as trading-up or the Porter hypothesis [76], clearly shows the interdependencies of the technological and political arena [77].

Yet, potentially even the two tipping dynamics in the political and technological sphere might not have been enough to trigger the encompassing change that led to the phasing out of CFCs, as another aspect of the process, namely a shift in social norms and thus the component of *behavioral tipping,* also played an important role. More precisely, once science clearly demonstrated the danger of CFCs and the immense consequences of ozone depletion for human health, e.g., skin cancer, the general public in several advanced industrialized countries became very sensitive to this issue, and the consumption of products that included CFCs, such as hairsprays, became stigmatized. This process was strongly reinforced by groups of concerned policymakers and atmospheric scientists, so-called epistemic communities, which, according to Haas [78], had a strong impact on bringing the topic to the forefront of public attention. Thus, this normative change towards not using CFCs anymore strongly affected the demand for these products and immensely increased pressure from the general public on national governments to enact appropriate (international) legislation [79].

This again shows how the different tipping dynamics interact with each other, this time behavioral tipping dynamics with political tipping dynamics (green and red circles in Fig. 1). On the one hand, public pressure was a crucial element in prompting unilateral policy change, especially in the U.S. [30]. On the other hand, the political sub-dynamics reinforced behavioral dynamics in that legislation in several front-runner states critically increased the awareness of the dangers inherent in the depletion of the ozone layer. Furthermore, consumers changed their shopping behaviors and opted for CFC-free products, creating another feedback loop and forcing companies to adapt to a changing demand.

Taken together, this short discussion of the phasing out of CFCs shows that while an analysis of each of the three sub-dynamics alone provides important insights, it is only their joint understanding, including their interrelations, as highlighted by the *social tipping dynamics framework,* that provides a complete account of the drastic change observed. Finally, while our framework, as shown in Fig. 1, incorporates many relevant aspects of social tipping dynamics in the case of CFCs, it is important to note that the scope conditions for tipping in the case of CFCs were probably much more advantageous than in the current case of climate change.[7] First, political tipping dynamics were facilitated by the fact that while multilateral policy change was the preferred option for important front-runner states, such as the U.S., also unilateral action was in their (economic) interests [74]. This is surely not the case for climate change, in which free-riding incentives often impede political tipping dynamics. Second, since the production of CFCs was concentrated in few countries, the material interests (depicted in the right upper part of Fig. 1) were much more conducive towards tipping than in the case of climate change, which concerns every country and almost all industrial sectors. Similarly, substitution technology had to cover only one type of product, i.e., CFCs, whereas, in the case of climate change, many technological innovations are necessary, making technological tipping dynamics much more difficult to materialize. Third and finally, in the case of ozone depletion, the necessary behavioral tipping dynamics were less substantive, as they mainly implied no longer buying products containing CFCs and increasing the pressure on elected politicians. However, in the case of climate change mitigation and adaptation, both aspects are much more difficult, thus implying higher hurdles for behavioral tipping. On the one hand, behavioral change will need to happen regarding many aspects of our lives, from consumption and leisure to travel and production. On the other hand, political pressure in favor of more stringent climate change politics is still met with considerable resistance in parts of the population. In summary, this is not to say that our proposed approach of studying tipping dynamics is futile in the context of climate change. To the contrary, our arguments demonstrate that for deep and profound change to happen in climate change politics, reinforcing tipping dynamics are likely necessary in all three sub-dynamics: political, behavioral, and technological.

[7] For a discussion of the interlinkage between the Montreal Protocol and climate change, see for instance [84].

5. Conclusion and outlook

The present article proposes a framework of social tipping dynamics to conceptualize and understand the specific type of fundamental societal change that is necessary for effective climate change mitigation [10,24], namely, change that on the one hand has sudden and drastic consequences on a "dependent variable," such as CO_2 emissions, and on the other hand is encompassing, i.e., involving the political, technological, and behavioral spheres. We show that previous theoretical approaches, such as path dependency, theories of the policy process, policy feedback, the Granovetter model, norm changes, and technological transition approaches *on their own* cannot explain *this* type of transformational change. Conversely, while the idea of social tipping seems to be suitable in this respect, existing research has mainly used it as an illustrative metaphor [[10], p. 2]; however, a conceptual framework is needed to make it useful also in analytical terms. We strive to fill this gap and propose a framework of social tipping dynamics that integrates the strengths of previous approaches and consists of three core elements. First, we suggest conceptualizing social tipping in terms of social tipping *dynamics* rather than a tipping *point*, the former being a more realistic account of how tipping in the social (in contrast to the natural) sphere occurs. Second, we claim that when using the notion of tipping in the social and political science context, unlike in the natural sciences, we can hardly identify the one single factor causing tipping, but in complex and endogenous societal and political systems, it is much more likely that various *sub-dynamics*—namely the political, technological, and behavioral—interact and together tip the system from one state to another. Third, we emphasize the role of *agency*. In contrast to natural tipping, actors relevant for social tipping dynamics act intentionally [26]. However, these actions might have the intention to trigger tipping, but also might hinder tipping and or have unintended consequences, as actors cannot foresee exactly what their actions will lead to. However, to better understand tipping itself, and also the processes that lead to it or prevent it, we need to specifically consider what actors think and do. Fourth and finally, we illustrate the merits of such a holistic perspective, integrating the different paths as well as the role of agency, using a real-world example. The CFC case illustrates that, whereas each sub-dynamic can trigger more encompassing tipping dynamics on its own, interlinkages between changing policies, new technologies, and changing norms and behaviors are highly relevant.

Our framework is stylized, but we argue that it can nevertheless spark a discussion on the empirical merits of the social tipping concept. While the social tipping dynamics framework specifies analytical paths for studying the type of change needed for effective climate mitigation and adaptation policy, it needs to be translated into suitable research designs (see [80]). In this vein, we see our framework as one important step towards empirical analysis. In terms of a future research agenda on social tipping, the framework can be applied to dynamics with differing geographical or sectoral impact, i.e., to study large-scale tipping dynamics (e.g., at the global level) but also more local tipping dynamics (e.g., phasing out one specific technology in one specific country). Therefore, the approach fits and integrates the idea of tipping cascades [81], i.e., interlinkages between different tipping dynamics at different levels. In this paper, we deliberately focus on social tipping dynamics that are normatively desirable [15], as we need to move away from fossil-fuel based technologies to reduce CO_2 emissions to meet the targets of the Paris agreement. However, the social tipping dynamics framework could also be used to describe normatively less desirable processes. Hence, we encourage researchers to distinguish between an analytical perspective and "desirable" social tipping. Moreover, the social tipping framework, emphasizing the links between the different spheres, might also be a useful tool to differentiate between situations where these interactions create non-linear change and those instances where only incremental or no change can be observed.

In conclusion, we argue that the social tipping dynamics framework offers several advantages for future research focusing on fundamental and accelerated societal change that impacts the socio-ecological Earth System. Whereas with respect to technological progress, the non-linearity of technological dynamics has been emphasized before, suggesting "breakthrough" dynamics that lead to changing paths [82], the concept of social tipping dynamics is useful to analyze and understand fundamental changes more broadly, i.e., not only in the technological but also in the behavioral and political sphere. It suggests that researchers might focus on the conditions under which tipping dynamics may evolve, i.e., enabling countries, industries, and individuals to leave their prevalent energy path. Thus, the framework includes the main catalysts of change: new policies, new technologies, and new behavioral norms. We suggest that this perspective is particularly useful to analyze and better understand ongoing energy transitions in many countries, and we encourage scholars to apply our framework to, for example, the rapid expansion of solar and wind power worldwide, aspirations to phase out coal and nuclear energy, and the transition to a transport system consisting of electric vehicles. Hence, with our framework, we hope to provide researchers a new useful tool for better understanding and explaining change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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