# Global warming overshoots increase risk of triggering climate tipping points and cascades

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# Global warming overshoots increase risk of triggering climate tipping points and cascades

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**Climate tipping elements play a crucial role for the stability of the Earth system under human pressures and are potentially at risk of disintegrating within and partially even below the Paris temperature guardrails of 1.5–2.0°C above pre-industrial levels. However, current policies and actions make it very likely to, at least temporarily, transgress the Paris targets. This raises the question whether tipping points can still be avoided under such overshoot scenarios. Here, we investigate the associated risks for tipping under a range of temperature overshoot scenarios using a stylised network model of four interacting climate tipping elements: the Greenland and West Antarctic Ice Sheets, the Atlantic Meridional Overturning Circulation and the Amazon rainforest. Our results reveal that temporary overshoots can increase tipping risks by up to 72% compared to a soft landing without overshoots, even when the long-term equilibrium temperature stabilises within the Paris range. Moreover, we find that modest interaction strength levels between the tipping elements are responsible for 49% more tipped elements than without cascading interactions. Our analysis shows that avoiding a *high climate risk zone*, which minimise risks for triggering tipping dynamics requires both long-term temperatures to stabilise at or below today's levels of global warming, and low temperature overshoots at the same time.**

It has long been proposed that important continental-scale subsystems of the Earth's climate system possess nonlinear behaviour[1,2]. The defining property of these tipping elements are their self-perpetuating feedbacks once a critical threshold is approached or transgressed[3] such as the melt-elevation feedback for the Greenland Ice Sheet[4] or the moisture recycling feedback for the Amazon rainforest[5]. Global mean surface temperature has been identified as the driving parameter for the state of the climate tipping elements[1,6,7], which include, among others, systems like the large ice sheets on Greenland and Antarctica, the Atlantic Meridional Overturning Circulation (AMOC), or the Amazon rainforest[8,9,10,11].

Besides further amplifying global warming[3], the disintegration of such climate tipping elements individually would have large consequences for the biosphere and human civilisations, including sea-level rise over very long time periods, large-scale biome shifts and collapses, or shifts of monsoon systems. Since the first mapping of climate tipping elements in 2008[1] the scientific focus has increased, with a 2019 warning that nine of the known 15 climate tipping elements are showing signs of instability[12], followed by a listing of all known climate tipping elements with levels of tipping point likelihoods in the IPCC AR6[13]. As this science has advanced temperature thresholds have been corrected downwards several times[12]. The most recent scientific assessment places the critical threshold temperatures of triggering tipping points at 1–5°C, with moderate risks already at 1.5–2°C for several systems, like the Greenland and the West Antarctic Ice Sheets[6]. In this sense, tipping elements research provides even further scientific support to hold global mean surface temperatures within the Paris range of 1.5–2°C, while at the same time emphasising the tipping point risks cannot be ruled out even at this lower temperature range[7].

There is thus a triple dilemma emerging here. First, insufficient policies and actions means that the world is following a trajectory well-beyond 2°C by the end of this century[14]. Second, essentially all IPCC scenarios that hold the 1.5°C line include a period of several decades of temperature overshoot[13]. And third, given that tipping elements research can no longer exclude crossing tipping points already at low temperature ranges (<2°C), more knowledge is urgently needed on risks of crossing tipping points during periods of overshoot[15,16,17].

Therefore, it is essential to assess the temperature overshoots and long-term temperature stabilisations that can lead to irreversible changes in the climate system. While the impacts of overshoots have been investigated from a mathematical point of view and a climate tipping element view for individual elements[15,18,19], climate tipping elements interact across scales in space and time, creating risks of additional feedback dynamics[12,20,21,22]. Interactions may increase tipping risks by triggering cascades, when tipping of one element triggers tipping of connected tipping elements[23]. Therefore in this work, we combine the research on interactions between climate tipping elements and temperature overshoots. In this study, we systematically assess the risk for tipping and identify a high climate risk zone, considering remaining uncertainties in the properties of the tipping elements and different global warming overshoot scenarios if Paris temperature targets are not met without overshoots.

## Simulation procedure of overshoots applied to tipping elements

Following Wunderling et al. (2021)[23], we use a stylised network model of ordinary differential equations designed for risks analysis to couple four climate tipping elements (see Methods): the Greenland Ice Sheet, the West Antarctic Ice Sheet, the AMOC, and the Amazon rainforest (see map in Fig. 1). In this model, the interactions between these tipping elements and the driving physical mechanisms are estimated on a formalised expert elicitation[22], enabling to assess cascading tipping risks at a certain level of global warming. Our network model is able to capture the main dynamics of these interacting tipping elements, and is therefore able to propagate important uncertainties in the input parameters. These include the critical temperature thresholds and the typical tipping time scales of the individual tipping elements, as well as the interaction strengths and interaction network structure. The low computational complexity of our approach allows to sample this parameter space by means of a very large-scale Monte Carlo ensemble simulation, including approximately 3.8 million individual ensemble members (model simulation runs) in total. For the construction of the ensemble, but also for the boundary values of the parameters uncertainties (based on the latest literature review[6]), see Methods.

In these numerical experiments, the four tipping element network is exposed to different global warming overshoot scenarios characterised by the peak temperature, duration of the overshoot, and the final convergence temperature reached in long-term equilibrium (see Fig. 1a). All these are important properties of the overshoot trajectory in determining the outcome of a potential tipping event. The stylised temperature overshoot trajectories applied to the four interacting climate tipping elements, were primarily designed to capture typical temperature profiles generated by Earth System Model simulations for low to medium emissions scenario[24]. Moreover, the formulation of the trajectories allows for flexibility in how society manages the transition from current warming to the convergence temperature, which can therefore lead to overshoot trajectories[15]. To this end, our ensemble spans all combinations of (i) peak temperatures $T_{\text{Peak}} = 2.0, 2.5, ..., 6.0$°C (maximally reached temperature), (ii) convergence temperatures $T_{\text{Conv}} = 0.0, 0.5, ..., 2.0$°C (final stabilisation temperature), and (iii) convergence times $t_{\text{Conv}} = 100, 200, ..., 1000$ years (time to reach $T_{\text{Conv}}$), allowing us to quantify the respective risk and time scale for tipping events. Not that the limit case of $T_{\text{Peak}} = T_{\text{Conv}} = 2.0$°C is simulated as constant temperature. In this paper, we will focus on peak temperatures up to 4.0°C, where 4.0°C represents an upper temperature limit we investigate, based on *policies and targets* following COP26 and the climate-action-tracker[14]. High-end warming scenarios with peak temperatures of 4.5–6.0°C are added in the supplementary material, which allow computing a comprehensive risk analysis. Fig. 1a presents an exemplary timeline of an overshoot trajectory that peaks at 2.5°C warming and converges to a 2.0°C convergence temperature after 400 years. The impact on the four studied interacting tipping elements is shown in Fig. 1b.

For this scenario, the global mean temperature (GMT) remains above the critical threshold of the Greenland Ice Sheet and therefore causes tipping. However, the Greenland Ice Sheet has a slow tipping time scale, while the melting trajectory is irreversible, taking over 1,000 years to transition to an ice-free state. Despite GMT briefly exceeding the AMOC critical threshold, this is not enough to cause the AMOC to tip initially. However, the Greenland Ice Sheet tipping causes the AMOC to tip later (on a faster timescale of roughly 100 years) due to the strong coupling between the two elements. Additionally in this scenario, the West Antarctic Ice Sheet tips as a result of both the Greenland Ice Sheet and the AMOC tipping. The tipping time scale of the West Antarctic Ice Sheet is slow and so with the Greenland Ice Sheet as the initiator, the overall tipping of the three elements takes 1,000 years to complete. Some further exemplary scenarios are provided in supp. Fig. S1. In the remainder of this work, the impact of a certain relevant parameter combination ($T_{\text{Peak}}$, $T_{\text{Conv}}$, $t_{\text{Conv}}$) on the risk of an element tipping is given by the fraction of all simulation runs that result in a tipped state, averaged over all other parameters and uncertainties. In this study, we define the tipping of an element as the tipping process being completed, i.e. when the tipping element reaches the transitioned regime (cf. Fig. 1b). In the remainder of this work, we first evaluate the tipping risk with respect to the overshoot peak temperature, convergence temperature and convergence time, and identify risk maps for a high climate risk zone. Second, we determine the mechanisms for tipping events and, third, we investigate the role of interactions and quantify the amount and share of tipping cascades.

### The effects of overshoot peak temperature

Focusing on the role of overshoot peak temperature, we find that the risk for the emergence of at least one tipping event increases with rising peak temperature. Averaged over all ensemble members, around one-third ($36.5\pm5.0\%$) of all simulations show a tipping event or cascade at a peak temperature of 2.0°C above pre-industrial, while it is close to three-quarters ($74.3\pm1.4\%$)

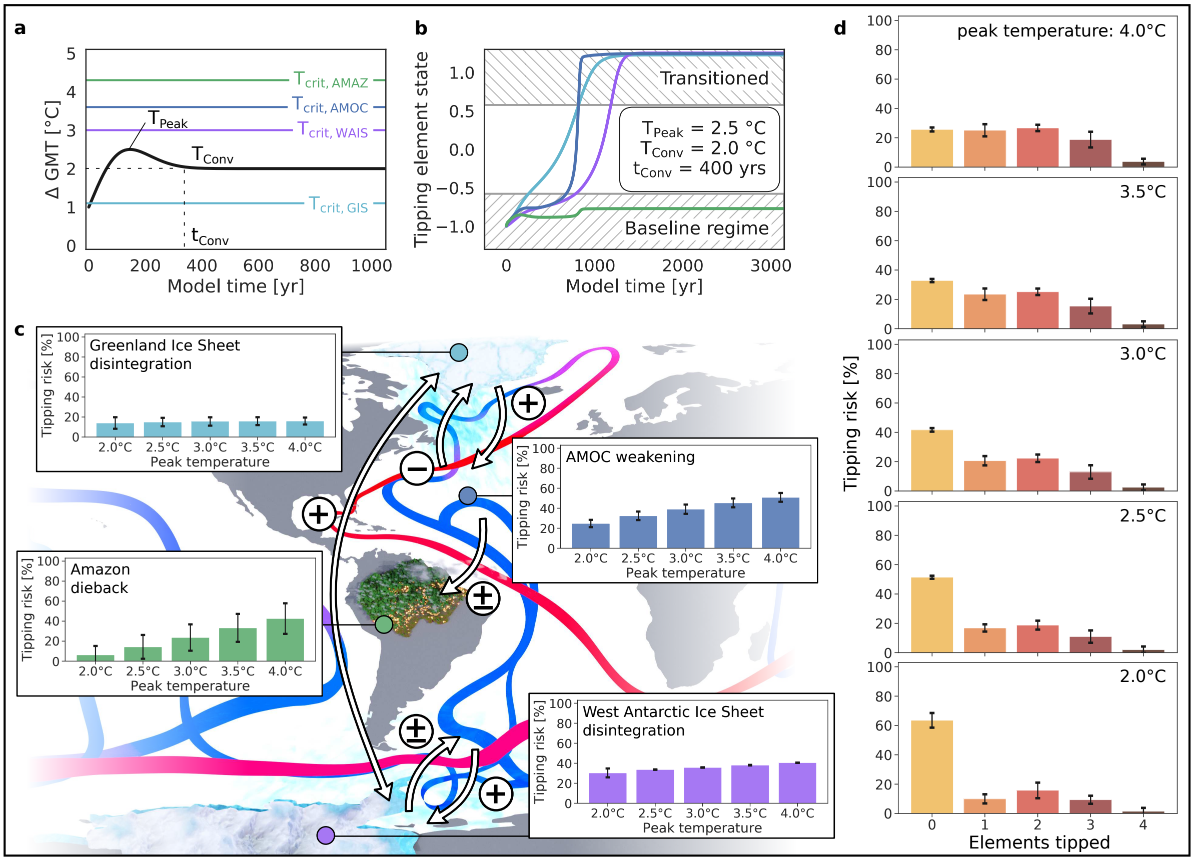


**Figure 1 | Effect of overshoots on interacting climate tipping elements. a,** Exemplary global warming overshoot scenario with a peak temperature of $T_{\text{Peak}} = 2.5°\text{C}$, a convergence temperature of $T_{\text{Conv}} = 2.0°\text{C}$ above pre-industrial, and a time to convergence to 2.0°C of $t_{\text{Conv}} = 400$ years. This scenario is applied to a set of four investigated interacting climate tipping elements. **b,** The effect of the overshoot trajectory shown in panel a: the Greenland Ice Sheet, the West Antarctic Ice Sheet and the AMOC tip. For further exemplary overshoot scenarios and the exact parameter values, see supp. Fig. S1. **c,** Map of four interacting climate tipping elements: Greenland Ice Sheet, West Antarctic Ice Sheet, AMOC and Amazon rainforest. The insets show the individual risk of transitioning into the undesired state in dependence of overshoot peak temperatures of 2.0–4.0°C above pre-industrial levels. **d,** Number of tipped elements in dependence of overshoot peak temperatures of 2.0–4.0°C above pre-industrial. The errors depict the standard deviation considering uncertainties in the interaction network structure. High-end overshoot peak temperatures up to 6.0°C above pre-industrial levels and tipping times (after 100 yrs, 1,000 yrs, and in equilibrium), are shown in supp. Fig. S2.

of all simulations at 4.0°C peak temperature (Fig. 1d). However, the dependence on the peak temperature is unevenly distributed among the four different climate tipping elements (see insets in Fig. 1c). The tipping risk for tipping elements with high inertia (slow tipping elements: Greenland and West Antarctic Ice Sheets) remains constant over an increasing peak temperature because their reaction time (500-13,000 years) is slow against the duration of the overshoot trajectory ($t_{\text{Conv}} = 100 - 1,000$ years). Therefore, e.g., the tipping risk for the Greenland Ice Sheet remains relatively constant between $T_{\text{Peak}} = 2.0$°C (tipping risk: 14.0±5.7%) and $T_{\text{Peak}} = 4.0$°C (tipping risk: 16.0±3.5%, see insets in Fig. 1c). In contrast, for tipping elements with low inertia (fast tipping elements: AMOC and Amazon rainforest) there is a strong tipping risk increase, comparing scenarios of $T_{\text{Peak}} = 2.0$°C (tipping risk of AMOC: 24.7±3.7%) with $T_{\text{Peak}} = 4.0$°C (tipping risk of AMOC: 50.8±4.4%, see insets in Fig. 1c). On the other hand, the tipping risk for the slow tipping elements increases for increasing convergence times (see supp. Fig. S3), whereas the tipping risk for the fast tipping elements only increases slightly for increasing convergence times above 200 years. This subsequent increase can largely be attributed to cascading effects, where typically the Greenland Ice Sheet tipping has initiated tipping on the faster elements. For peak temperatures above 5.5°C, it becomes highly likely (virtually certain, i.e. >95%) that at least one tipping element transitions to its alternative state (see supp. Fig. S2). Fig. 1 shows the equilibrium results after 50,000 simulation years, which demonstrate the long-term commitment due to transgressed tipping thresholds. While this provides an important insight into potential locked-in change, some tipping risks are already realised after 100–1,000 years. On these shorter time scales, especially the AMOC and the Amazon rainforest show a strong dependence on the peak temperature (see supp. Fig. S2). Especially for the West Antarctic Ice Sheet, new literature results suggest lower temperature thresholds as before[6,7]. Therefore, considerable tipping risks (30.3±4.5%) can be observed already at peak temperatures of 2.0°C (see Fig. 1c insets).

## Risk maps for identifying a high climate risk zone

For final convergence temperatures comparable with today's levels of warming (approx. $T_{\text{Conv}} = 1.0°\text{C}$), we find that the expected number of tipped elements is at least $< \# >_{\text{tipped,min}} = 0.29$ (see Fig. 2). This minimal number of tipped elements is evaluated for the most optimistic case of this study (lowest-left parameter combination in Fig. 2a, b, c), where the peak temperature reaches 2.0°C above pre-industrial and the convergence time to the final temperature is 100 years. The tipping risk that at least one tipping element transitions to its alternative state (related to $< \# >_{\text{tipped,min}} = 0.29$) is 15%, see Fig. 2d. Stabilising global warming at the lower limit of the Paris range at 1.5°C above pre-industrial levels, increases the number of minimally tipped elements to 1.19, and for a stabilisation at the upper Paris limit of 2.0°C, we find at least 1.89 tipped elements on average (compare Fig. 2a, b, c).

Going from the number of tipped elements to tipping risks, we define a *high climate risk zone* as the region, within which the likelihood for no tipping event to occur is larger than 66%, or the risk that one or more elements tip is lower than 33%. We compute this risk and find an increase from 15% over 56% to 82% at convergence temperatures of 1.0, 1.5 and 2.0°C for the most optimistic parameters ($t_{\text{Conv}} = 100$ years and $T_{\text{Peak}} = 2.0°\text{C}$, compare Fig. 2d, e, f). These results lead to the conclusion that the high climate risk zone spans the entire state space for final convergence temperatures of 1.5–2.0°C. Only if final convergence temperatures are limited to, or better below, today's levels of global warming, while peak temperatures are below 3.0°C, the tipping risks remain below 33% (see Fig. 2d). In parallel, the equipotential lines shift strongly from higher peak temperatures and convergence times to lower ones with increasing convergence temperature. This leads to a lower likelihood of low-risk scenarios without tipping elements transitioning to their alternative state. In the worst case of a convergence temperature of 2.0°C (see Fig. 2f), the tipping risk for at least one tipping event to occur is on the order of

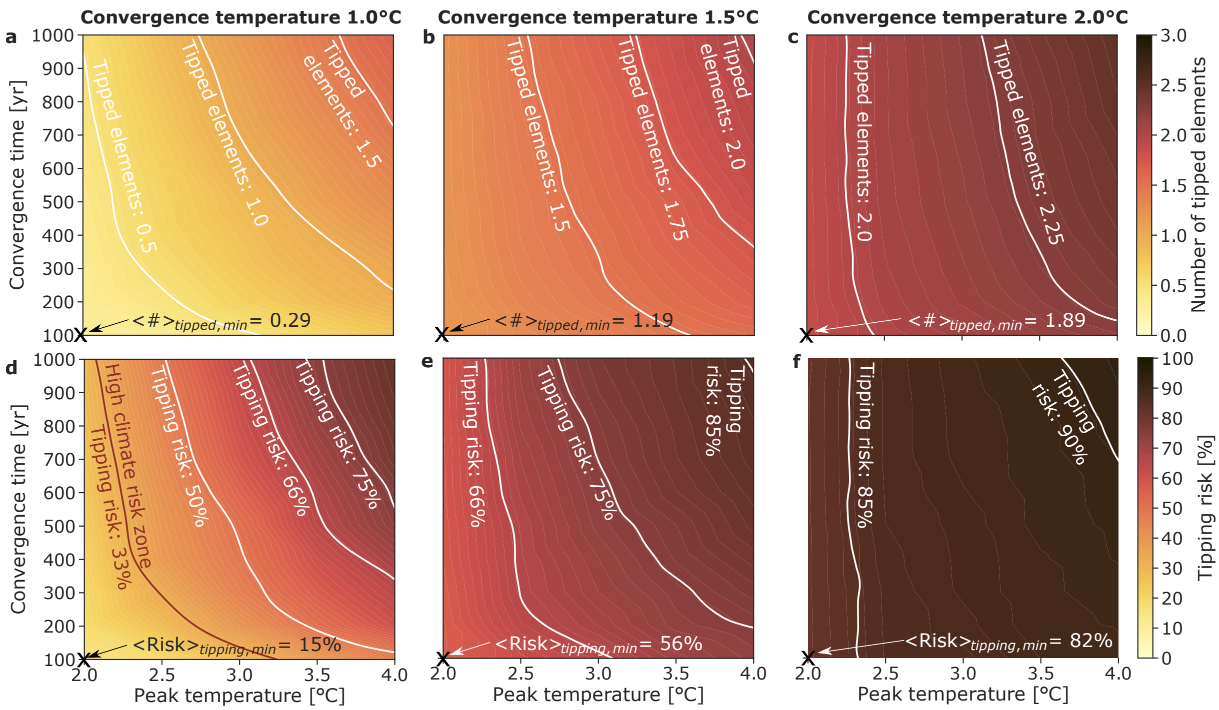


**Figure 2 | Expected number and risk of tipping events at different convergence temperatures.** **a,** Number of tipped elements averaged over the entire ensemble for all investigated convergence times $t_{\text{Conv}} = 100, 200, ..., 1000$ years and peak temperatures $T_{\text{Peak}} = 2.0, 2.5, ..., 4.0$°C at a convergence temperature of $T_{\text{Conv}} = 1.0$°C above pre-industrial levels. The white lines show the conditions at which 0.5, 1.0, and 1.5 elements are tipped on average. $< \# >_{\text{tipped, min}}$ is the average number of tipped elements at $t_{\text{Conv}} = 100$ years and $T_{\text{Peak}} = 2.0$°C, which is the most optimistic case. **b, c,** Same as in **a**, but for convergence temperatures of 1.5°C and 2.0°C, respectively. Note that the white equipotential lines denote 1.5, 1.75 and 2.0 tipped elements in panel **b**, and 2.0 and 2.25 tipped elements in panel **c**. **d,** The risk that at least one tipping element transitions to its alternative state at the end of the simulation (after 50,000 simulation years, equilibrium simulation) for a convergence temperature of 1.0°C. The equipotential line in red indicates the *high climate risk zone* (tipping risk is equal to 33%), while the further white lines indicate risks of 50%, 66% and 75%, respectively. $<$ Risk $>_{\text{tipping , min}}$ is the average risk of at least one element being tipped at $t_{\text{Conv}} = 100$ years and $T_{\text{Peak}} = 2.0$°C. **e, f,** Same as for **d**, but for convergence temperatures of 1.5°C and 2.0°C, respectively. Note that the equipotential lines indicate 66%, 75% and 85% (panel **e**), and 85% and 90% (panel **f**) that at least one element is tipped. The simulations for $T_{\text{Conv}} = 0.0$°C (return to pre-industrial temperatures) and $T_{\text{Conv}} = 0.5$°C can be found in supp. Fig. S4. High-end scenarios with $T_{\text{Peak}}$ =4.0–6.0°C are added in supp. Figs. S5 and S6.

above 90% if peak temperatures of 4.0°C are not prevented. So, considering all the uncertainties in the ensemble, only less than 10% of the ensemble members remain free of tipping events in this case. The devastating negative consequences of such a scenario with high likelihood of triggering tipping events would entail significant sea level rise, biosphere degradation or considerable North Atlantic temperature drops.

Therefore, this would entail an *unsafe overshoot* regime. On the other hand, strictly lowering the final convergence temperature of or below today's levels of global warming while limiting peak overshoot temperatures to 3.0°C and convergence times in parallel significantly reduces the risk of tipping events (see Fig. S4 and Fig. 2d). In the most optimistic scenario, tipping risks are kept below 5%.

**Tipping mechanisms and timing under current climate trajectories**

The risk for tipping events increases with higher peak temperatures, higher convergence temperatures, and longer convergence times. However, the mechanism causing a tipping event to occur in our model is twofold: (i) The element tips due to the final temperature $T_{\text{Conv}}$ being higher than its critical temperature threshold. We call this *baseline tipping* because the final baseline, i.e. the convergence temperature, is already higher than the critical temperature. An example for baseline tipping for the Greenland Ice Sheet can be found in Fig. 1a, b. (ii) The element tips due to the temperature overshoot trajectory, which temporarily transgresses its critical temperature threshold. We call this *overshoot tipping*. In both cases, baseline tipping or overshoot tipping, the first tipped element can draw along other elements in a tipping cascade such that the size of the cascade is not necessarily restricted to one. We compute that the risk for tipping events occurring at convergence temperatures within the limits of the Paris climate target ranges between slightly more than half (57.8%) to more than nine-tenths (91.4%) of all simulations (see Fig. 3). For small peak temperatures ($T_{\text{Peak}} = 2.5$°C), overshoot tipping only accounts for as little as 9% of all tipping events but for intermediate peak temperature levels ($T_{\text{Peak}} = 4.0°\text{C}$) this number can increase to as much as 42% (see pie charts in Fig. 3). Specifically, the risk of tipping increases between 10–72% in these scenarios for overshooting before stabilising at the convergence temperature than just approaching the convergence temperature with no overshoot. Note that in the special case, where the peak temperature equals the convergence temperature ($T_{\text{Peak}} = T_{\text{Conv}} = 2.0°\text{C}$), overshoot tipping events do not occur.

The number of expected tipping events increases from short to long time scales as tested in our experiments, where we separated tipping events realised after 100 (short-term tipping), 1,000 (mid-term tipping) and 50,000 simulation years (equilibrium tipping, see bar charts in Fig. 3). For higher peak temperatures, we additionally observe a larger portion of tipping events realised within 100 and 1,000 years. These short-term events are dominantly caused by the fast tipping elements (AMOC and Amazon rainforest), but mid-term events are additionally also partially caused by a tipping West Antarctic Ice Sheet (see supp. Fig. S2). Together our results indicate that in order to avoid tipping events within the Paris range, not only the peak temperature must be limited but also the final convergence temperature must fall significantly below 1.5°C in the long run. This would reduce the tipping risk to 8.8–23.4% if final convergences temperatures range between 0.0–1.0°C and $T_{\text{Peak}} = 2.0°\text{C}$ (see supp. Fig. S7). To further hedge these tipping risks, the time to reach the convergence temperature must also be small (i.e. $t_{\text{Conv}} \lesssim 200$ yrs, cf. supp. Fig. S4c,d). However, current *policies and action* would lead to 2.0–3.6°C (mean: 2.7°C), and present *pledges and targets* to 1.7–2.6°C (mean: $2.1°\text{C}$) above pre-industrial, based on the COP26-update published in November 2021 (see climateactiontracker and vertical axis in Fig. 3c)[14] as expected temperatures in 2100. As noted above, these temperatures would lead to significant tipping risks if they were interpreted as peak temperatures. If they would be convergence temperatures, tipping very likely is unavoidable. Additionally, high-end scenario simulations with very high peak temperatures between 4.5–6.0°C reveal that the risk to observe tipping becomes virtually certain (>95% for $T_{\mathrm{Peak}} \gtrsim 5.5°\mathrm{C}$). At these scenarios, it is likely (>40%) that the first tipping event would occur within 100 years, typically the Amazon rainforest or the AMOC (see supp. Fig. S8).

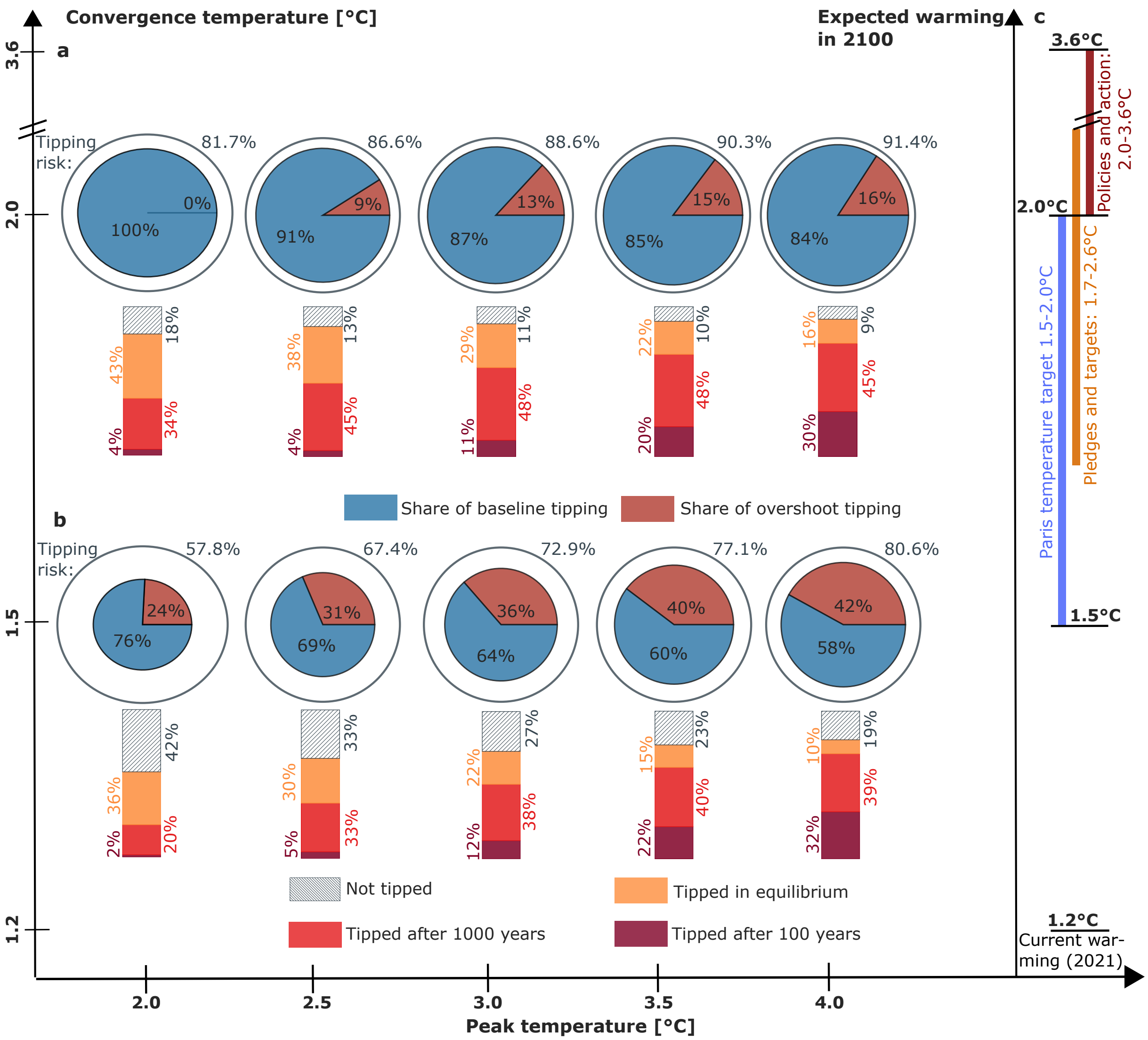

**Figure 3 | Mechanisms and timing of tipping events following a temperature overshoot.** Here, we show the risk for tipping with respect to overshoot scenarios of 2.0–4.0°C and convergence temperatures within the Paris range of 1.5–2.0°C above pre-industrial. The size of the *pie-chart* indicates the overall tipping risk (e.g. 67.4% at $T_{\mathrm{Conv}}$=1.5°C and $T_{\mathrm{Peak}}$=2.5°C). The number of observed tipping events can be separated into two mechanisms: (i) due to the convergence temperature being above the critical temperature for one or several tipping elements (*baseline tipping*, example see Greenland Ice Sheet in Fig. S1d, e), and (ii) due to the overshoot trajectory (*overshoot tipping*, example see AMOC in Fig. S1c). The *bar chart* directly below the pie-chart splits the tipping events into the time-scale when they occur. Either after 100 simulation years (dark red), 1,000 simulation years (light red), in equilibrium simulations (after 50,000 simulation years, orange), or not at all (hatched). **a,** Scenario where global mean temperature converges to 1.5°C. **b,** Scenario where global mean temperature converges to 2.0°C. **c,** Expected warming in 2100 after the COP26 *pledges and targets* (orange vertical line: 1.7–2.6°C), and the *policies and action* (dark red vertical line: 2.0–3.6°C) together with the current warming of 1.2°C and the Paris temperature target (blue vertical line: 1.5–2.0°C). Note that the vertical axes are nonlinear due to visibility. The data for the vertical lines has been compiled from the November 2021 update by climateactiontracker[14]. The scenarios with lower convergence temperatures of 0.0, 0.5, and 1.0°C above pre-industrial are depicted in supp. Fig. S7. High-end climate scenarios and overshoots for peak temperatures between 4.5–6.0°C are shown in supp. Fig. S8.

## The role of interactions and cascading effects

An interesting aspect, which has not been investigated before, are the effects of interactions on the risk of (cascading) transitions in overshoot scenarios. The average number of tipped elements increases with increasing interaction strength (see Fig. 4). Here, an interaction strength of 0.0 represents four individual uncoupled tipping elements, while an interaction strength of 1.0 represents the case where the interactions are approximately as important as the individual dynamics[23]. For convergence temperatures of 1.5 or 2.0°C, we find a notable effect of increasing number of tipped elements due to cascading interactions between interaction strength values of 0.0–0.3. The total effect at a convergence temperature of 1.5°C increases the average tipped number from 1.04±0.04 at an interaction strength of 0.0 to 1.46±0.03 at an interaction strength of 0.3, corresponding to an increase of 40.4±3.9%. For a convergence temperature of 2.0°C, the increase of the average number of tipped elements makes up an additional 49.3±2.1%. In this case, a further increase of the interaction strength from 0.3 to 1.0, only leads to a marginal additional tipping risk of 12.1±0.5%. The reason for this nonlinear increase in tipping at low to moderate interaction strength levels are cascading transitions because higher convergence temperatures cause more tipping cascades than lower convergence temperatures (compare Fig. 4a with Fig. 4b, c). This effect is most clearly apparent in the equilibrium effects over a long time scale (orange bars), while time scales up to 1,000 years show a relatively linear increase of tipped elements with increasing interaction strength (red bars), and in contrast to a nearly constant number of tipped elements for time scales up to 100 years (dark red bars). This implies that the interactions between climate tipping elements require a significant amount of time for their effect to be observable in the number of tipped elements. This can be explained by the roles of the tipping elements in cascading transitions. It has been found in earlier research that the slow tipping elements (Greenland and West Antarctic Ice Sheet) are the main initiators of cascading transitions[23], but they also need the largest amount of time to commence a transition, the effects of which can then be transported to further tipping elements (AMOC and Amazon rainforest) via the respective physical interactions. Therefore, the role of interactions, and with that the amount of tipping cascades, can most clearly been seen for the long-term equilibrium experiments (see orange bars in Fig. 4). Lastly, it is notable that the proportion of equilibrium tipping events goes down with decreasing convergence temperature (see Fig. 4). For convergence temperatures of 0.0, 0.5,and 1.0°C above pre-industrial levels, elements tipped in equilibrium do not play a role because in these latter scenarios the number of baseline tipping scenarios is insignificantly small and overshoot tipping does only rarely occur for the slow tipping elements (see supp. Fig. S9).

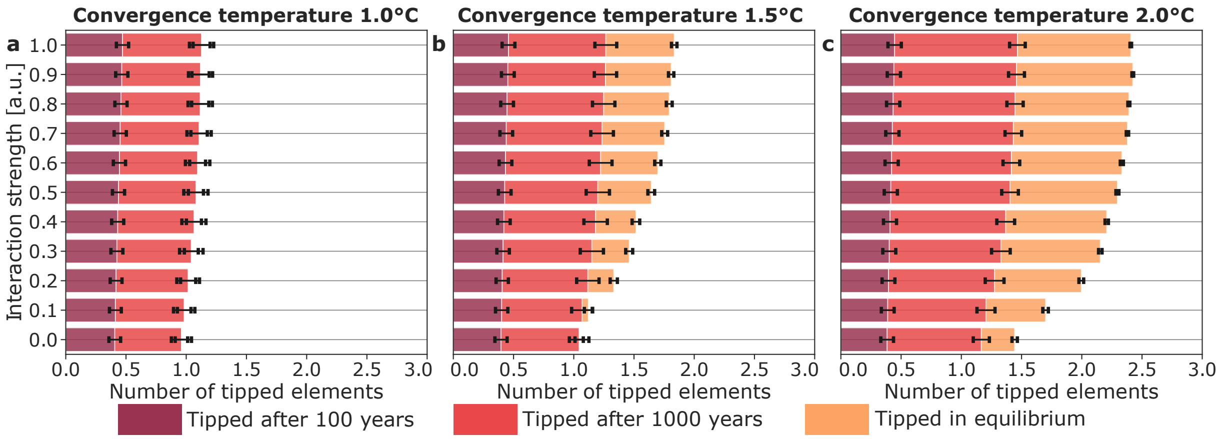


**Figure 4 | Effect of interaction strength between climate tipping elements.** Number of tipped elements against the interaction strength, separated into the respective tipping times (dark red: tipped after 100 simulation years, red: tipped after 1,000 simulation years, orange: tipped in equilibrium after simulation 50,000 years) for a convergence temperature of **a,** 1.0°C, **b,** 1.5°C and **c,** 2.0°C above pre-industrial levels. The errors show the standard deviation over the different interaction network realisations. For convergence temperatures of 0.0°C and 0.5°C above pre-industrial levels, see supp. Fig. S9.

## Discussion

In summary, we find that the high climate risk zone characterised by large tipping risks (>33%) can only be avoided if several aspects are met in parallel due to the different time scales involved. These aspects are limited overshoot peak temperatures, limited convergence times, and most importantly limited convergence temperatures (due to baseline tipping) to levels at, or better, below the current level of global warming (1.2°C)[14]. Our analysis shows that the overshoot peak temperature should be constrained based on fast tipping elements (see Fig. 1c), whereas slow tipping elements largely determine the upper limit for convergence times (see supp. Fig. S3). The convergence temperature needs to be limited to avoid baseline tipping, and lower levels of it will also assist in avoiding overshoot tipping (see Fig. 3). Therefore, the combination of the slow Greenland Ice Sheet having a low temperature threshold and the faster elements (AMOC, Amazon rainforest) having at least partially higher thresholds (see supp. Tab. S1), facilitates the possibility of a small overshoot without causing tipping events and thus further cascades. Ritchie et al. (2021)[15] came to similar conclusions for individual tipping elements but we find, for a sufficient interaction strength, a marked increase in the expected number of tipped elements in equilibrium due to the possibility of emerging tipping cascades (see Fig. 4). Taken together, safe and unsafe temporary overshoot trajectories can clearly be separated.

Our employed stylised network model does not directly capture physical processes in its differential equations, and can as such not be used as a model for predictions, but has been designed as a risk assessment tool for some of the most nonlinear entities in the Earth system. The choices of our stylised global warming overshoot scenarios are motivated by current knowledge, summarising short and long-term effects. The shape of the short-term overshoot trajectories captures the temperature profiles from different Earth system model simulations[24], but is still of conceptualised nature (see Eq. 2). To allow for a direct comparison to the baseline critical temperatures, we keep the temperature trajectories at constant levels in the long run. While this is supported by ZECMIP (Zero Emissions Commitment Model Intercomparison Project) for the near- to intermediate future for decades to centuries[25,26], it is unclear how carbon sinks and sources behave for the more distant future. On time scales of centuries to millennia, it seems more likely than not that a slight downward trend of global mean temperatures will be entered[26,27,28]. Still, large uncertainties remain and make future research necessary as has for instance been proposed by using a novel framework of model experiments for zero emission simulations[29]. Overall, it is questionable whether this effect of naturally decreasing temperatures would be sufficient to bring global mean temperatures after an overshoot back down to safe levels without additional artificial carbon removal from the atmosphere[28].

A benefit of low complexity models such as ours is that they allow for very large-scale Monte Carlo ensemble simulations, which can take into account relevant uncertainties such as in interaction structure, strength and critical temperature thresholds. One prominent example, which we consider in our Monte Carlo ensemble, is the uncertainty on the interaction of the AMOC with the Amazon rainforest, which could either be negative, positive or zero[22], leading to relatively large tipping risk errors for the Amazon rainforest (see insets of Fig. 1c). In principle, our model is also flexible enough such that new tipping elements and their interaction structure can be added, or it can be easily re-run to include updated knowledge on the tipping elements, if necessary. Still, it should be aimed at building more complex models around coupled nonlinear phenomena and climate tipping elements, either by combining simple physics-based models and combining those models with observational data[30,31,32], or by employing Earth System Models of either intermediate or high complexity. In the latter case, tipping elements could be spatially resolved, which might refine or modify some of the results gained here[33]. Moreover, data-based approaches should be considered, with which it might be possible to reconstruct actual interaction strength values. This might be possible using machine learning techniques based on remote sensing data or, potentially, could be similar to already available investigations on nonlinear changes in the Earth system[34,35]. Recently, it has also been proposed to combine these two research strands, with data-based approaches making use of artificial intelligence and Earth system modelling, to create "neural" Earth system models[36].

Critically, to reduce the risk and prevent the negative impacts of interacting climate tipping elements on human societies and biosphere integrity, it is of utmost importance to ensure that temperature overshoot trajectories are limited in both magnitude and duration, while stabilising global warming at, or better, below the Paris agreement's targets. Concretely, avoiding a high climate risk zone aiming to limit the risk for tipping events would entail convergence temperatures of today's levels of global warming or below ($< 1.2$°C, better $\lesssim 1.0$°C), while overshoot temperatures should not exceed 3.0°C and convergence times should not exceed 300 years unless peak temperatures are significantly smaller than 2.5°C. This would reduce the risk for one tipping event to occur to below 33% (see Fig. 2d). Although our results motivate that a future climate trajectory without or with limited temperature overshoots would be preferable, current results from the COP conferences and their pledges and targets indicate that at least temporary overshoots over the Paris range seems likely[14,37]. This would not only be problematic because of natural risks exerted by disintegrated climate tipping elements, but also economic damages would be smaller in case of a no-overshoot scenario, as has been shown in recent literature[37,38]. Even without overshoots though, economic damages could be tremendous due to the irreversible nature of climate tipping elements and their interactions[39,40,41].

## Methods

**Interacting climate tipping element model.** We use the stylised network model designed for risk analysis of four interacting tipping elements detailed in Wunderling et al. (2021)[23]. Each tipping element is described by the following differential equation

$$\frac{dx_i}{dt} = \left[ -x_i^3 + x_i + \sqrt{\frac{4}{27}} \cdot \frac{\Delta\mathrm{GMT}(t)}{T_{\text{crit, i}}} + d \cdot \sum_{\substack{j \\ j \neq i}} \frac{s_{ij}}{10} \left( x_j + 1 \right) \right] \frac{1}{\tau_i}. \tag{1}$$

Here, $x_i$ describes the state of the respective tipping element $i = \mathrm{GIS},\ \mathrm{AMOC},\ \mathrm{WAIS},\ \mathrm{AMAZ}$ (GIS: Greenland Ice Sheet, AMOC: Atlantic Meridional Overturning Circulation, WAIS: West Antaractic Ice Sheet, AMAZ: Amazon rainforest). This differential equation possesses two different stable states: a baseline regime around $x_i \approx -1.0$ and a transitioned regime around $x_i \approx +1.0$. $\Delta\mathrm{GMT}(t)$ denotes the global mean surface temperature increase above pre-industrial levels (as compared to the 1850–1900 level). This term is time dependent because of the time dependence of the overshoot trajectory, which serves as our input: $\Delta\mathrm{GMT}(t) = \text{overshoot trajectory}(t)$. The mathematical form of the overshoot trajectory is given below in the methods section: *temperature overshoot trajectories*. $T_{\text{crit, i}}$ denotes the critical temperatures for the four tipping elements. The interaction strength parameter is indicated by $d$ and is varied between 0.0 and 1.0, where $d = 0.0$ means no interaction between the tipping elements and $d = 1.0$ means that interactions are approximately as important as the individual dynamics. The link strength $s_{ij}$ is taken from an expert elicitation[22]. Lastly, the time scale-parameter $\tau_i$ denotes the tipping time of a particular tipping element. Of course, the four stylised differential equations above (Eq. 1) are a strong simplification of the more complex tipping elements. However, they represent a summary of the main stability patterns, as has been argued in literature before[23,42]. For more details on the mathematics in this model, please be referred to Wunderling et al.(2021)[23].

**Parameter uncertainties.** There are uncertainties in several parameters of the model (see Eq. 1 and supp. Tab. S1): (i) In the critical temperature regimes $T_{\text{crit, i}}$, which are taken from the recently refined literature values[6]. (ii) The interactions between the climate tipping elements all represent physical mechanisms behind each pair of tipping elements. For instance a melting Greenland Ice Sheet induces a freshwater input into the North Atlantic and, by that, weakens the AMOC, while a weakening AMOC would reduce the warming over Greenland (see Fig. 1). There is a considerable uncertainty of the link strength parameters $s_{ij}$, which are included in our uncertainty analysis, and their values are taken from an expert elicitation on interacting climate tipping elements[22]. The same values for interaction strengths have been used in earlier research on tipping cascades[23]. (iii) The upper and lower bounds for tipping times for the four tipping elements are again taken from recent literature[6]. It is important to note that the timescales for tipping vary from decades, over centuries up to millennia depending on the respective tipping element. While the Amazon rainforest and the AMOC tip on shorter timescales (decades to centuries), the Greenland and West Antarctic Ice Sheets take longer to disintegrate (multiple centuries to millennia). These, on at least two orders of magnitude, different tipping times have important effects on the dynamics of tipping, and as to whether a specific tipping event occurs or not. These effects are discussed in the main text.

**Propagation of uncertainties via a Monte Carlo ensemble.** Since there are considerable uncertainties in the critical temperature regimes, interaction strengths and structure, as well as in the tipping time scales, we set up a large-scale Monte Carlo ensemble to adequately propagate the uncertainties in these parameters. The uncertainty range of the parameter uncertainties are given in supp. Tab. S1. For each combination of peak temperature ($T_{\text{Peak}} = 2.0, 2.5, ..., 6.0$°C), convergence temperature ($T_{\text{Conv}} = 0.0, 0.5, ..., 2.0$°C) and convergence time ($t_{\text{Conv}} = 100, 200, ..., 1000$ years), we draw 100 realisations from a continuous uniform distribution using a latin hypercube algorithm[43] over the uncertainties in critical temperatures, link strengths and tipping times. These 100 realisations are looped over the 9 possible different network structures ([i] a positive link between WAIS→AMOC and a positive link between AMOC→AMAZ, [ii] a zero link between WAIS→AMOC and a positive link between AMOC→AMAZ, ..., [ix] a negative link between WAIS→AMOC and a negative link between AMOC→AMAZ). With this procedure, we obtain approximately 3.8 million ensemble members in total. By drawing from a continuous uniform distribution for all tipping elements, we slightly overestimate the overall uncertainties and perform a maximum uncertainty assessment. Therefore, our errors are conservative. After 100 years, 1,000 years and in equilibrium (here: 50,000 years), we branch off the results for each of our 3.8 million ensemble members such that we can assess our results at these three different timings.

**Temperature overshoot trajectories.** In this study, we have used stylised temperature overshoot trajectories based on overshoot trajectories that capture temperature profiles generated by Earth System Model simulations for a low to medium emissions scenario[24]:

$$\Delta\mathrm{GMT}(t) = T_0 + \gamma t - \left[1 - \mathrm{e}^{-(\mu_0 + \mu_1 t)t}\right]\left[\gamma t - (T_{\mathrm{Conv}} - T_0)\right]. \tag{2}$$

In this equation, the temperature overshoot trajectory $\Delta\mathrm{GMT}(t)$ is determined via five parameters: (i) $T_0$ is the approximate current level of global warming, i.e. the point at which the trajectories start at $t = 0$. We have chosen $T_0 = 1.0$°C above pre-industrial levels. (ii) $T_{\mathrm{Conv}}$ is the final convergence temperature, for which we have chosen an ensemble approach comprising $T_{\mathrm{Conv}} = 0.0, 0.5, 1.0, 1.5, 2.0$°C above pre-industrial. (iii) The parameter $\gamma$ is chosen such that the global warming rate matches the recent past. The exponential decay term describes the development away from the linearly increasing trend (set by $\gamma$) bent towards the stabilisation level (set by $T_{\mathrm{Conv}}$), specified by the parameters (iv) $\mu_0$ and (v) $\mu_1$. In our ensemble, we construct a temperature overshoot trajectory with a specific peak temperature $T_{\text{Peak}}$ and convergence time $t_{\text{Conv}}$ by iteratively altering the parameters $\gamma$, $\mu_0$ and $\mu_1$ until it matches the desired peak temperature and convergence time. Exemplary overshoot trajectories can be found in supp. Fig. S1, where the chosen parameters correspond to Fig. 1a. The chosen parameter values to get $T_{\text{Peak}} = 2.5°\text{C}$ and $t_{\text{Conv}} = 400$ years are: $\gamma = 0.0963°\text{C}\,\text{yr}^{-1}$, $\mu_0 = 1.5 \cdot 10^{-3}\,\text{yr}^{-1}$, and $\mu_1 = 1.83 \cdot 10^{-4}\,\text{yr}^{-2}$. The convergence temperature is set to $T_{\text{Conv}} = 2.0°\text{C}$. The accuracy we require for our scenarios is $\Delta T_{\text{Peak}} < 0.025°\text{C}$ and $\Delta t_{\text{Conv}} < 0.5$ years, where the convergence time is determined as the time when the temperature overshoot curve has reached the convergence temperature to an accuracy of $0.01°\text{C}$.

**Notes on colour maps.** This paper makes use of perceptually uniform colour maps developed by F. Crameri[44].

**Data and Code availability.** The data and code that support the findings of this study are available from the corresponding authors upon reasonable request. The python modelling package *pycascades*, with which we simulated the dynamics of interacting tipping elements, is available at `https://pypi.org/project/pycascades/`, together with a model description paper[45]. In case of questions or requests, please contact N.W..

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## Author contributions

R.W., J.R. and J.F.D. conceived the study. N.W. designed the study, performed the simulations and led the writing of the manuscript with input from all authors. N.W., S.L. and B.S. prepared the figures with input from R.W., J.R. and J.F.D.. J.F.D. led the supervision of this study.

## Additional information

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## Competing interests

The authors declare no competing interests.

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