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Fast energy transitions can reduce climate tipping risks

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Abstract

Exceeding 1.5°C warming is now unavoidable, which increases the risk for triggering climate tipping elements. Although ambitious mitigation and carbon dioxide removal might still reduce these risks, the extent of feasible risk reduction remains unclear. Here, we couple three models—the 3-machines energy transition model, the FaIR climate emulator, and the conceptual model for interacting tipping elements PyCascades—to simulate tipping probabilities of four climate tipping elements. With this model pipeline, we quantify the probability of triggering climate tipping elements under fastest-possible, yet technically feasible energy transitions that return to 1.0°C warming. We find that, relative to following current policies, the mean probability of tipping at least one element could still be reduced from 5.8% to 0.1% over the next 100 years and by 78.0 percentage points over the next 50,000 years. Besides lowering tipping probabilities, starting fast energy transitions earlier may also delay tipping events by centuries, providing more adaptation time to adverse tipping impacts. Keeping long-term tipping probabilities below 0.5% would require limiting peak warming to 2.0°C and returning 0.8°C or lower in the long-term.

1 Introduction

Drawing on a variety of different lines of evidence ranging from paleo-climate studies, Earth system model-based analyses to observational studies and expert assessments, several Earth subsystems have been identified that could undergo critical transitions to alternative stable states under ongoing warming.^{1–6} These tipping elements include the disintegration of the Greenland Ice Sheet (GIS) and the West Antarctic Ice Sheet (WAIS), as well as a weakening of

the Atlantic Meridional Overturning Circulation (AMOC), and the dieback of the Amazon rain forest (AMAZ) among others.¹ These transitions are sustained by self-amplifying feedback and sometimes exhibit hysteresis such that reversing them would generally require stronger cooling than the warming that triggered the change.^{7,8}

Crossing the 1.5°C threshold—which recent research suggests is now unavoidable⁹—increases the likelihood of triggering tipping elements, such as the Amazon rain forest (critical temperature: 1.5–6.0°C).^{10,11} To date, climate change has already imposed substantial ecological, financial, and social costs,^{12–15} and some systems may already have crossed critical thresholds. For example, mass bleaching events during 2023–2025 indicate that warm-water coral reefs have likely reached their thermal tipping point (central estimate: 1.2°C (1.0–1.5°C) warming), committing them to 70–90% loss¹ and directly affecting roughly 500 million people who depend on them.¹⁶

The consequences of tipping further climate elements would be severe. For example, the collapse of the AMOC could lead to global food instability due to extreme and prolonged winters in North-west Europe and heat accumulation in the Southern Hemisphere.¹⁷ Likewise, destabilizing GIS could commit to around 7 m and WAIS to an additional 3–5 m of sea-level rise,^{7,18} exposing those living in low-lying coastal regions to escalating flood risk and displacement (currently around one billion people¹⁹). Beyond cryosphere changes, the AMAZ—home to about 10% of global terrestrial biodiversity and many indigenous communities—also plays a central role in Earth’s carbon cycle²⁰ and the South American water cycle;²¹ an Amazon dieback into a savanna-like state would therefore have profound ecological, social and climatic repercussions. Given these stakes, the international community emphasized at COP27 in Egypt the need to improve understanding of tipping dynamics and develop strategies to minimize tipping probabilities.²²

The relevance of these climate tipping elements has prompted researchers to estimate tipping probabilities resulting from mitigation pathways. After early efforts using expert elicitation,²³ subsequent work deepened and collected the process understanding of individual tipping elements (e.g. thresholds and hysteresis of ice sheets),^{6,7,24–30} and more recently employed system dynamic models that explicitly capture interactions between tipping elements and the forcing effect of control variables (e.g. temperature).^{5,31,32} Across different models, studies agree that current policies imply a high risk of triggering one or more tipping elements.^{32,33}

However, two limitations complicate the interpretation of these results. First, much of the literature has concentrated on the hazards implied by current trajectories, leaving the potential for reducing irreversible risks of climate change under more ambitious transition scenarios underexplored. Second, mitigation pathways are typically specified only until 2100 and then extended into the forthcoming centuries using simplified assumptions about the timing of net-zero and subsequent net-negative emissions.^{33,34} Because tipping probabilities are sensitive to the overshoot duration,⁵ simplified post-2100 extensions may bias risk estimates by artificially shortening or lengthening the period of elevated temperatures.

The temperature trajectories beyond 2100 are shaped by the scale and persistence of carbon dioxide removal (CDR), yet the potential for CDR is highly uncertain (see Discussion section). Direct air capture and carbon storage (DACCS) is frequently expected to contribute significantly to CDR^{35,36} (up to 540 Gt CO₂ over the 21st century in 1.5°C compatible pathways³⁶), yet, the deployment of such an energy-intensive technology at scale³⁷ (thermodynamic minimum of 125 kWh per ton CO₂³⁸) is constrained by the evolution of the energy system itself,³⁹ a coupling that is often treated only implicitly or omitted. Moreover, most transition scenarios to date consider CDR mainly to compensate hard-to-abate emissions, and in some scenarios also to revert overshoot above 1.5°C. These scenarios do not explore the option space for faster, physically possible (yet highly ambitious) transitions to <350 ppm.³⁹ Robust assessments of post-2100 tipping probabilities therefore require energy transition models that explicitly represent large-scale CDR, including the associated energy and infrastructure requirements, over the forthcoming centuries.

To fill these gaps, we examine how much tipping probabilities can be reduced under mitigation pathways with highest physically possible ambitions (see Fig. 1 for Method overview). We use the 3-Machines energy transition model^{39,40} to generate highest-ambition, yet technically feasible energy transition pathways until 2300. Unlike common integrated assessment models (IAMs), the speed of transitions in the 3-machines model is constrained only by the feedback between energy supply and the energy investment required to deploy transition technologies, such as solar and wind infrastructure, grid storage, or direct air capture devices, while satisfying societal energy demand. The fastest, energy-constrained pathways limiting societal energy demand to about twice the energy needed to satisfy basic needs for all^{41,42} and minimal additional grid storage capacity⁴³ may achieve net-zero emissions within 2–14 years after starting the transition and allow returning to 1.0°C before 2300.³⁹ These pathways may approximate the physically feasible upper bound on how quickly global temperatures can be returned to safer levels. The point in time when a fast transition is initiated, i.e. when the emission pathway starts to deviate from current policies, can be chosen. We discuss the structural simplifications implemented in the 3-Machine model—such as the absence of energy sub-technology resolution and the exclusion of bioenergy with carbon capture and storage (BECCS)—in the Discussion section. In addition to energy-related emissions, we add emissions from agriculture, forestry, and land-use resulting (AFOLU) from ambitious C1 and C2 pathways in IPCC Assessment Report 6 (AR6)⁴⁴ and translate the resulting emission pathways into temperature trajectories with the FaIR v2.2.3 climate emulator⁷ (Fig. 2a). Finally, we assess tipping probabilities

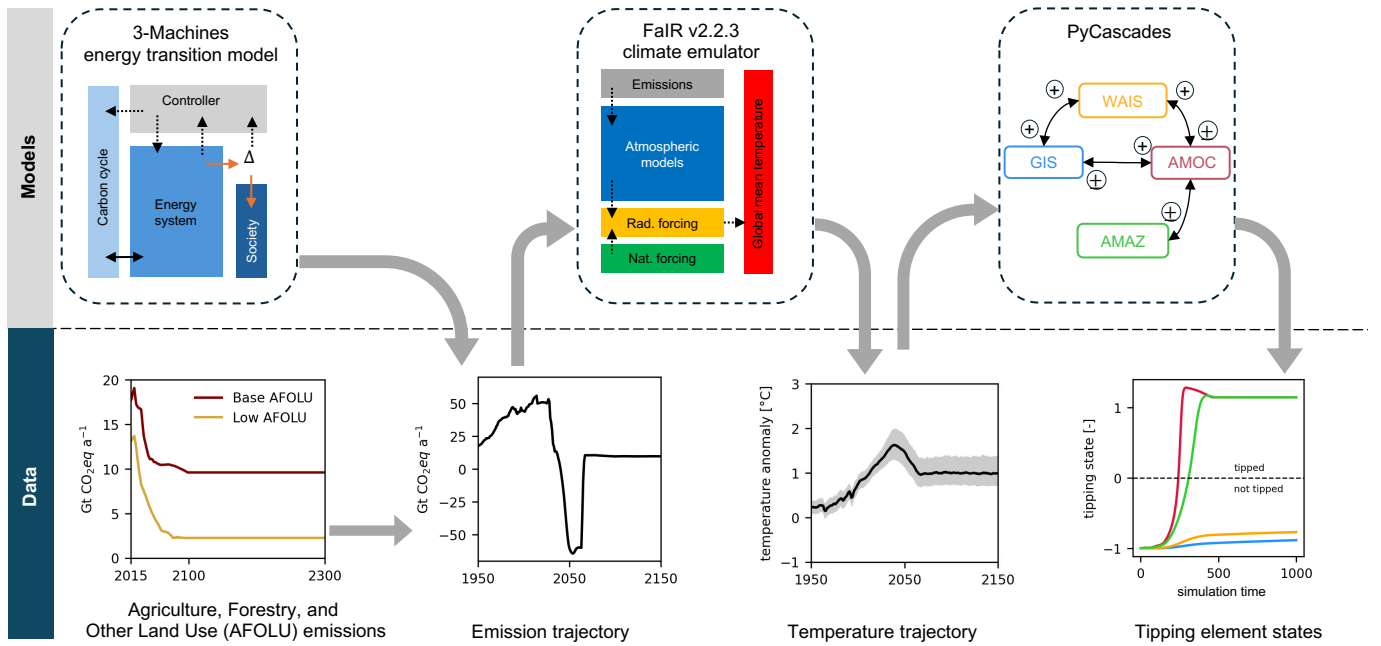


Figure 1: **Method overview.** Energy-related emission outputs of the 3-Machine energy transition model^{39,40} are paired with two distinct emission scenarios from agriculture, forestry, and other land use (AFOLU; 'base', 'low'; see Method section for details) from the AR6 database.⁴⁴ The aggregated emissions (until 2300) are converted to temperature trajectories using the FaIR v2.2.3 climate emulator⁷ and extended over 50,000 years at constant 2300 temperature levels. Temperatures trajectories are fed into the PyCascade model³¹ determining the tipping states for four tipping elements over time. GIS=Greenland Ice Sheet, AMOC=Atlantic Meridional overturning circulation, WAIS=West Antarctic Ice Sheet, AMAZ=Amazon rain forest.

for four tipping elements (GIS, AMOC, WAIS, AMAZ) using an updated version of the climate tipping network model PyCascades³¹ (Code availability section; see Discussion section for justifications for excluding other possible tipping elements). To capture uncertainty in greenhouse-gas climate sensitivity, tipping-network structure, coupling strengths among tipping elements, tipping timescales and critical temperatures (Fig. 2b), and tipping element interactions (Fig. 2c), we test an ensemble comprising more than 18 million individual realizations. Finally, we benchmark the resulting tipping probabilities against a Current Policies scenario that converges to 2.7°C heating⁴⁴ (Fig. 2a).

2 Methods

2.1 Baseline scenario

As our Current Policies baseline, we adapt the *EN NPi2020 3000* scenario from the REMIND-MagPIE 2.1-4.2 model.^{44–46} Because this scenario is designed until 2100, we linearly extrapolate decarbonization until reaching net-zero CO₂ emissions in 2120 and assuming no net-negative emissions thereafter. This yields an approximately constant temperature after the peak (median temperature of 2.8°C). The scenario's median warming in 2100 (2.7°C) is consistent with the 2.5–2.9°C warming range recently projected for Current Policies in the year 2100.⁴⁷

2.2 Energy transition model

We generate fast energy transition pathways using the 3-Machines energy transition model.^{39,40} The model designs pathways that achieve a target atmospheric CO₂ concentration under energy supply constraints. In a stylized representation of the global energy system, energy is supplied by fossil and renewable "machines", both of which require energy investments to build and maintain capacity (energy feedback). After meeting a selected level of societal energy demand, remaining energy can be allocated to expand the energy system or to operate a carbon

removal "machine". Emissions from the fossil machine and carbon removal change the stock of carbon accumulated in the atmosphere and upper oceans, which corresponds to both atmospheric CO₂ concentration and global mean temperature. The model can be parameterized to follow different strategies—for example, prioritizing fossil versus renewable build-out, allowing additional societal consumption, or timing carbon removal during versus after the transition. We run the model across parameter sets (Supplementary data) previously shown to enable short times to reach net-zero and to return atmospheric CO₂ concentrations below 350 ppm.^{39,40}

These fast transitions rely on five main strategies:³⁹ (i) reducing societal energy demand to sufficiency levels to free energy capacity to be invested in building renewable energy infrastructure and carbon removals; (ii) prioritizing expansion of solar on the built environment, given its large technical potential within Earth-system limits;⁴⁸ (iii) minimizing energy storage requirements through demand alignment, because additional energy demand for manufacturing storage infrastructure slows the transition;³⁹ and (iv) operating carbon removal only after fossil fuels are phased out, avoiding the inefficiency of removing carbon while simultaneously emitting it.

Recent extensions of the 3-Machine energy transition model indicate that material-energy feedback (e.g. aluminium availability) can further limit the speed of the energy transition by introducing material constraints. Here, we neglect material-energy coupling, because under optimal conditions (e.g. material substitution) material-energy-constrained pathways converge to the corresponding energy-constrained pathways.⁴⁰ Focusing on energy feedback alone therefore likely still provides a feasible upper limit on how fast energy transitions can be.

To include all relevant emissions from the energy system, we extend the 3-Machines model by accounting for sulfur and methane emissions from fossil fuel use in addition to CO₂, as these species contribute substantially to net radiative forcing.⁴⁹ The model then produces timeseries of energy-related CO₂, methane, and sulfur emissions, for the starting years 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050, 2075, and 2100 which we subsequently combine with non-energy-related emissions.

2.3 AFOLU scenarios

To account for non-energy emissions in our energy transition pathways, we add AFOLU emissions from C1 and C2 scenarios included in AR6 (230 scenarios targeting 1.5°C warming or lower).⁴⁴ As our baseline AFOLU case, we use the 95th percentile of C1/C2 AFOLU emissions, which yields near-constant post-transition temperatures (Supplementary Fig. 1). To test sensitivity to stronger AFOLU mitigation, we also consider one 'low' AFOLU case based on median AFOLU emissions in the C1/C2 scenario. We do not include AFOLU emission scenarios that would lead to a long-term temperature increase, as it would be inconsistent with the narrative of fast transition and large-scale carbon removal represented in our pathways.

We combine each AFOLU case ('base', 'low') with 20 energy transition scenarios (two long-term temperature targets, 1.0°C and 1.5°C; and ten transition start years), together with historical emissions. Together with one Current Policies scenario, this yields 41 distinct emission pathways spanning 1850–2300. Supplementary Figure 1 and 2 show the resulting temperature and emission trajectories.

2.4 Temperature conversion

We convert each emissions pathway into a global mean temperature timeseries for 1850–2300 using the FaIR climate emulator (v2.2.3).⁵⁰ The emulator is calibrated to reproduce historical emissions and is parameterized with an equilibrium climate sensitivity of 2.96°C per CO₂ doubling (5–95% range: 2.01–4.99°C).⁵¹ All underlying parameters are provided in this work's data and code repository.

To propagate uncertainty in the climate sensitivity, we sample the emulator's temperature distribution at the 10th to 90th percentiles in decile steps, yielding nine temperature trajectories per emission pathway (369 temperature timeseries in total). Because mean tipping timescales can be as long as 15,000 years (for the GIS), we extend each temperature trajectory by an additional 50,000 years by holding temperatures constant at their 2300 level, ensuring the system can reach an equilibrium tipped (or untipped) state.

2.5 Climate tipping network model

The dynamics of the four tipping elements are modeled in a stylized network model using a set of coupled ordinary differential equations^{5,31} as in Eq. 1:

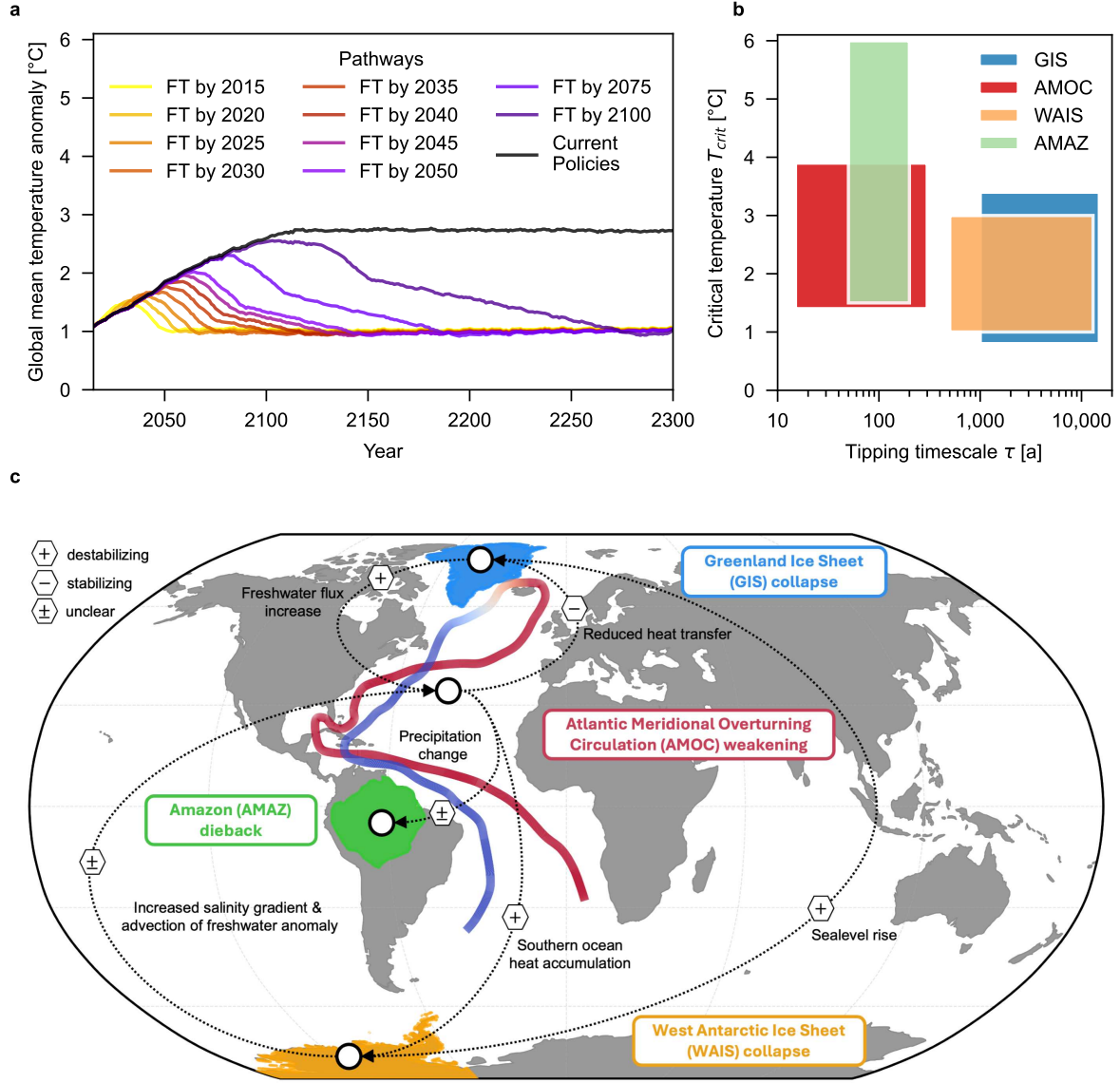


Figure 2: **Inputs to the PyCascades climate tipping model.** **a**, Temperature timeseries of investigated fast transition (FT) scenarios converging to 1.0°C and Current Policies (median of temperature trajectories). Temperature anomalies are relative to the 1850–1900 global mean temperature average. Fast energy transitions shown here are paired with the base AFOLU emission scenario. For the full decile range of temperatures, additional trajectories assuming low AFOLU emissions, or pathways converging to 1.5°C , see the Supplementary Figure 1. **b**, Critical temperature ranges above pre-industrial levels for triggering four tipping elements and the timescale of their transitions from the non-tipped to the tipped state. **c**, Interactions between four tipping elements: the Greenland Ice Sheet (GIS), the Atlantic Meridional Overturning Circulation (AMOC), the Amazon rain forest (AMAZ), and the West Antarctic Ice Sheet (WAIS).

$$\frac{dx_i}{dt} = \left[-x_i^3 + x_i + \sqrt{\frac{4}{27}} \frac{\Delta\text{GMT}(t)}{T_{\text{crit},i}} + d \sum_{j \neq i} s_{ij} (x_j + 1) \right] \frac{1}{\tau_i} \quad \forall i, j \in [\text{GIS}, \text{AMOC}, \text{WAIS}, \text{AMAZ}] \quad (1)$$

with x_i being the state of the tipping element i (GIS, AMOC, WAIS, or AMAZ), t the time, ΔGMT being the global mean temperature anomaly relative to the 1850–1900 average, $T_{\text{crit},i}$ the critical temperature of i , d the interaction strength between tipping elements, s_{ij} the link strength between the tipping element pair i and j , and τ_i the tipping

timescale for i .

Equation 1 is bistable, with two stable equilibria at $x \approx -1.0$ (non-tipped) and $x \approx +1.0$ (fully tipped), consistent with the stability structure proposed for the four tipping elements in the literature.^{31,52} We initialize each element at $t = 0$ in the non-tipped regime ($x \approx -1.0$). The first three terms in Eq. 1 describe the intrinsic dynamics of element i , forced by global warming relative to its critical temperature $T_{\text{crit},i}$. The fourth term is the coupling term, which represents interactions among tipping elements. The parameter d scales the overall interaction strength: $d = 0$ implies no interactions; $d = 1$ implies interactions are of comparable magnitude to the intrinsic dynamics. Values $d > 1$ would make interactions dominant, such that tipping of one element would almost inevitably trigger tipping cascades. Because palaeo-climate evidence does not support such near-inevitable global cascades,⁵³ we restrict $d \leq 1$ and sample $d \in [0, 0.1, \dots, 1.0]$ in each model run. The coefficients s_{ij} encode the relative strength of individual physical links between elements (representing a physical interaction mechanism, Supplementary Table 1), based on expert elicitation;²³ for each link we sample within its elicited range.

To propagate uncertainties in critical temperatures, tipping timescales, and link strengths, we run a Monte Carlo ensemble ($N=500$) using Latin hypercube sampling to draw parameter sets for the network model. Combining 369 temperature time series with 500 Monte Carlo draws, eleven values of d , and nine network configurations (reflecting stabilizing, destabilizing, or no interactions between AMOC and AMAZ as well as WAIS and AMOC) yields $369 \times 500 \times 11 \times 9 = 18,265,500$ simulations.

For evaluation, we classify each element as tipped ($x_i > 0$) or non-tipped ($x_i \leq 0$) at three time horizons: 2125 (short-term; 100 years from today), after 10,000 years (medium-term), and after 50,000 years (long-term). For each of the 41 emissions pathways, we first average tipping outcomes over 891 realizations per Monte Carlo draw (9 temperature percentiles $\times$ 11 interaction strengths $\times$ 9 network configurations) to obtain a pathway-level tipping probability. We then compute the mean tipping probability as the average of these pathway-level probabilities across the 500 Monte Carlo draws.

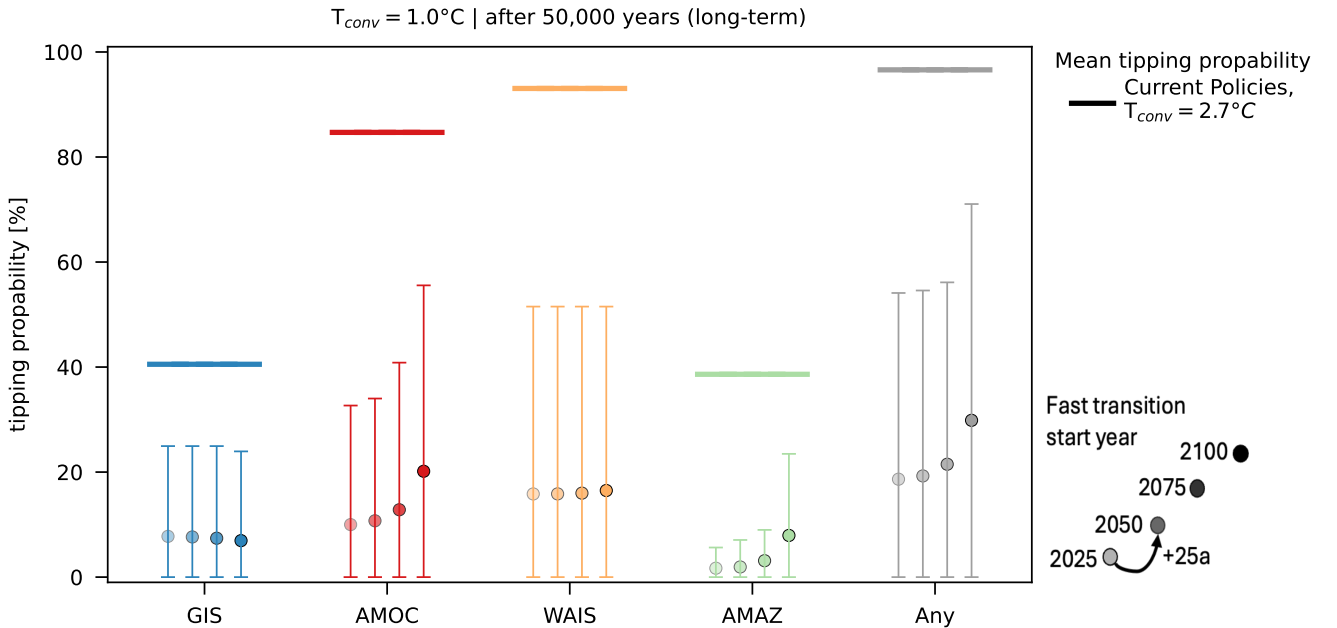


Figure 3: **Achievable tipping probabilities.** Mean tipping probabilities for fast energy transitions aiming at 1.0°C and starting either in 2025 (leftmost data point in group) or in 25 year time steps until 2100 (rightmost point). Error bars show 10th to 90th percentile of tipping probability across samples ($N=500$) spanning possible critical temperatures, tipping timescales, and link strengths. GIS=Greenland Ice Sheet, AMOC=Atlantic Meridional overturning circulation, WAIS=West Antarctic Ice Sheet, AMAZ=Amazon rain forest. 'Any' shows the probabilities for triggering at least one tipping element. The horizontal lines mark the mean tipping probabilities of Current Policies as the baseline.

3 Results

3.1 Tipping probabilities

First, we examine the tipping probabilities of a fast energy transition starting in 2025 compared to following Current Policies, finding that fast energy transitions can drastically reduce the long-term tipping probability compared to Current Policies⁴⁷ (Fig. 3).

Over the long-term (after 50,000 years), the highest reduction in tipping probability is achieved for WAIS, from 93.1% mean tipping probability in the Current Policies scenario to 15.8% (0–51.5%; 10th to 90th percentile) under a fast energy transition (starting in 2025). Second are reductions for AMOC tipping, from 84.7% under Current Policies to 10.0% (0–32.7%) under a fast transition, followed by 38.6% and 40.5% (under Current Policies) for AMAZ and GIS being reduced to 1.7% (0–5.6%) and 7.8% (0–24.9%), respectively, under a fast transition. Aggregated, the mean probability of tipping at least one tipping element ('Any') drops by 78.0 percentage points, from 96.6% under Current Policies to 18.6% (0–54.1%) when starting a fast transition in 2025.

Tipping probabilities are lower over medium time horizons (over the next 10,000 years). For a fast energy transition starting in 2025, the mean probability of triggering at least one tipping element within the next 10,000 years is 7.6% (0–18.2%), which is 11.1 percentage points below the corresponding long-term risk (Supplementary Fig. 3). In contrast, medium-term tipping probability under Current Policies remains high (mean of 90.4%, 6.2 percentage points lower than the long-term value). This medium-term reduction is primarily driven by the Greenland and West Antarctic ice sheets (GIS and WAIS) as they require several millennia to tip.

In the short-term, when following Current Policies over the next 100 years, only AMOC and AMAZ exhibit tipping, with mean tipping probabilities of 4.6% and 1.3%, respectively ('Any' with 5.8%, Supplementary Fig. 4). Yet, when diverging from Current Policies in 2025, following a fast transition instead, the short-term mean tipping probability for both of these decline to 0.1% and zero, respectively.

We investigate pathways aiming at 1.0°C, proposed as a safe long-term limit^{54–56} and considerably lower than the international political consensus of limiting global warming to below 2°C, preferably to 1.5°C.⁵⁷ If fast energy transitions would instead aim at the politically enshrined 1.5°C temperature goal, the long-term mean tipping probability would be 57.0% (12.1–100%) (for tipping at least one tipping element, and starting a fast transition in 2025, Supplementary Fig. 5), still a mean tipping probability reduction of 39.6 percentage points compared to Current Policies. However, compared to aiming at 1.0°C, this would lead to an increase of 38.4 percentage points in the long-term mean tipping probability (Supplementary Fig. 5; for short- and medium-term risks, Supplementary Fig. 6 and 7).

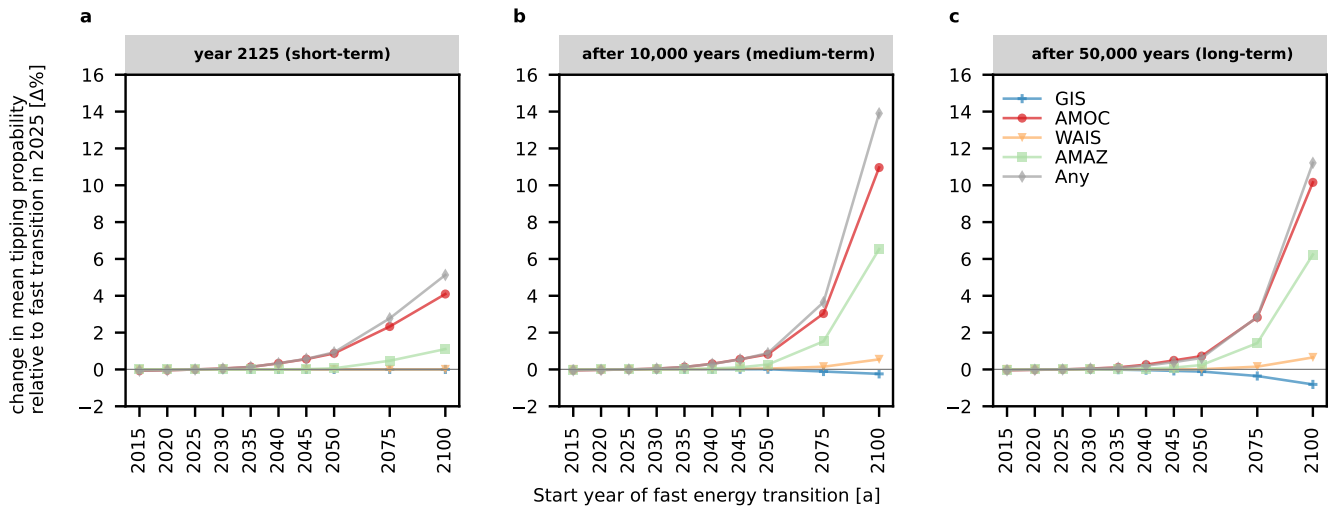


Figure 4: **Tipping probability increase from delaying a fast energy transition.** Change in mean tipping probability from delaying a fast energy transition compared to starting in 2025 for the **a)** short-, **b)** medium-, and **c)** long-term. The fast energy scenarios are returning to $T_{conv}=1.0^{\circ}\text{C}$. 'Any' refers to the probability of tipping at least one tipping element.

3.2 Tipping probabilities increase when delaying fast transitions

Since ambitious action might not materialize within the next years, we further assess the consequences of postponing a fast energy transition by as late as 2100 (Fig. 3 and Fig. 4) and following the Current Policies pathway until then (Fig. 2a).

Relative to a fast transition starting in 2025 (mean short-term tipping probability: 0.1%; long-term: 18.6%), delaying the start to 2050 has only a small effect on tipping probability, increasing the probability of triggering at least one element to 1.0% in the short-term and 19.3% in the long-term (Fig. 4a). Yet, tipping probability significantly rise with delaying fast transitions beyond 2050 (Fig. 4a–c). For example, while the mean of medium-term tipping probabilities increase by only 0.4 percentage points per decade until 2050 (for triggering at least element), risks start to increase sharply beyond the first half of the century by 1.1 between 2050 and 2075 and by 4.0 percentage point per decade from 2075 to 2100, respectively. In other words, delaying action in the second half of the century could be up to ten times worse compared to delays in the first half of the century.

The increasing tipping probability is driven by higher peak temperatures and longer overshoots with the delay of starting a fast transition, which mostly affects the AMOC and the AMAZ due to their short tipping timescales (15–300 and 50–200 years, respectively). The tipping probabilities of the ice sheets are affected less by transition delay (<1.0 percentage point increase from 2025 to 2100) due to the long tipping timescales. The mean tipping probability for the GIS is even slightly decreasing (–0.8 percentage point from a start in 2025 to 2100) due to regional cooling caused by AMOC weakening (Fig. 2c).

3.3 Earlier and faster transitions postpone tipping occurrences

Beyond reducing tipping probability, starting a fast energy transition early provides society with time to get adapted to the new conditions since—even if it might not fully prevent a tipping event—it does postpone it over time relative to the Current Policies scenario. We demonstrate this by showing the median year of tipping events under fast energy transitions compared to Current Policies (Fig. 5). Under Current Policies, the AMAZ is the earliest element to tip (median tipping year: 2329). In contrast, with a fast energy transition starting in 2025 the median tipping year for the AMAZ is delayed by almost 12 000 years. Second to tip is the AMOC (Current Policies median tipping year: 2450), yet, under fast transitioning in 2025, the median tipping year is delayed by almost 13 000 years compared to Current Policies. The WAIS and the GIS tip last (median tipping year: ~7 700 and ~11 000, respectively), but fast energy transitions can postpone both their median tipping years by around 10 000 years. Delaying the onset of the fast transition from 2025 to 2050 leads to earlier AMOC and AMAZ tipping: just a 25-year delay in starting a fast transition brings median AMOC tipping by 1 600 years and median Amazon tipping by more than 3 000 years closer. In contrast, delaying the energy transition leads to slightly later GIS tipping due to the stabilizing interaction with a weakened AMOC (reduced heat transfer to the northern Atlantic).

3.4 Sensitivity to AFOLU emissions

After phasing out fossil fuels, AFOLU emissions may remain. Reduction in these non-energy-related emissions are strongly linked to future dietary choices and agricultural practices, which are culturally dependent and consequently uncertain. We therefore test the robustness of our results under different assumptions regarding AFOLU emissions (Supplementary Fig. 8). In our base AFOLU scenario, emissions converge to a level of around 80% of today's AFOLU emissions (currently 11.9 Gt CO_{2,eq} per year⁵⁸). When assuming long-term AFOLU emissions at the median rate of C1/C2 climate mitigation scenarios ('low' AFOLU, ca. 20% of today's AFOLU emissions), tipping probabilities under fast energy transitions could be reduced further due to lower convergence temperatures (0.6°C (0.4–1.0°C) under 'low' AFOLU emissions). More precisely, the long-term mean tipping probability for tipping at least one in four elements would be 2.1% (0–7.1%), a mean tipping probability reduction of 16.5 percentage points compared to the base AFOLU case (starting year 2025; 13.5–16.5 percentage points depending on the starting year), suggesting that long-term tipping probability can be even lower under more ambitious AFOLU scenarios (i.e., when temperatures converge to lower than 1.0°C).

3.5 A safe operating space for mitigation pathways

The level of residual climate-tipping risk that society is willing to accept effectively determines the required mitigation ambition. Figure 6a maps tipping probability as a function of two variables: peak warming and the long-term convergence temperature. For comparison, European insurance companies are required to hold sufficient capital to

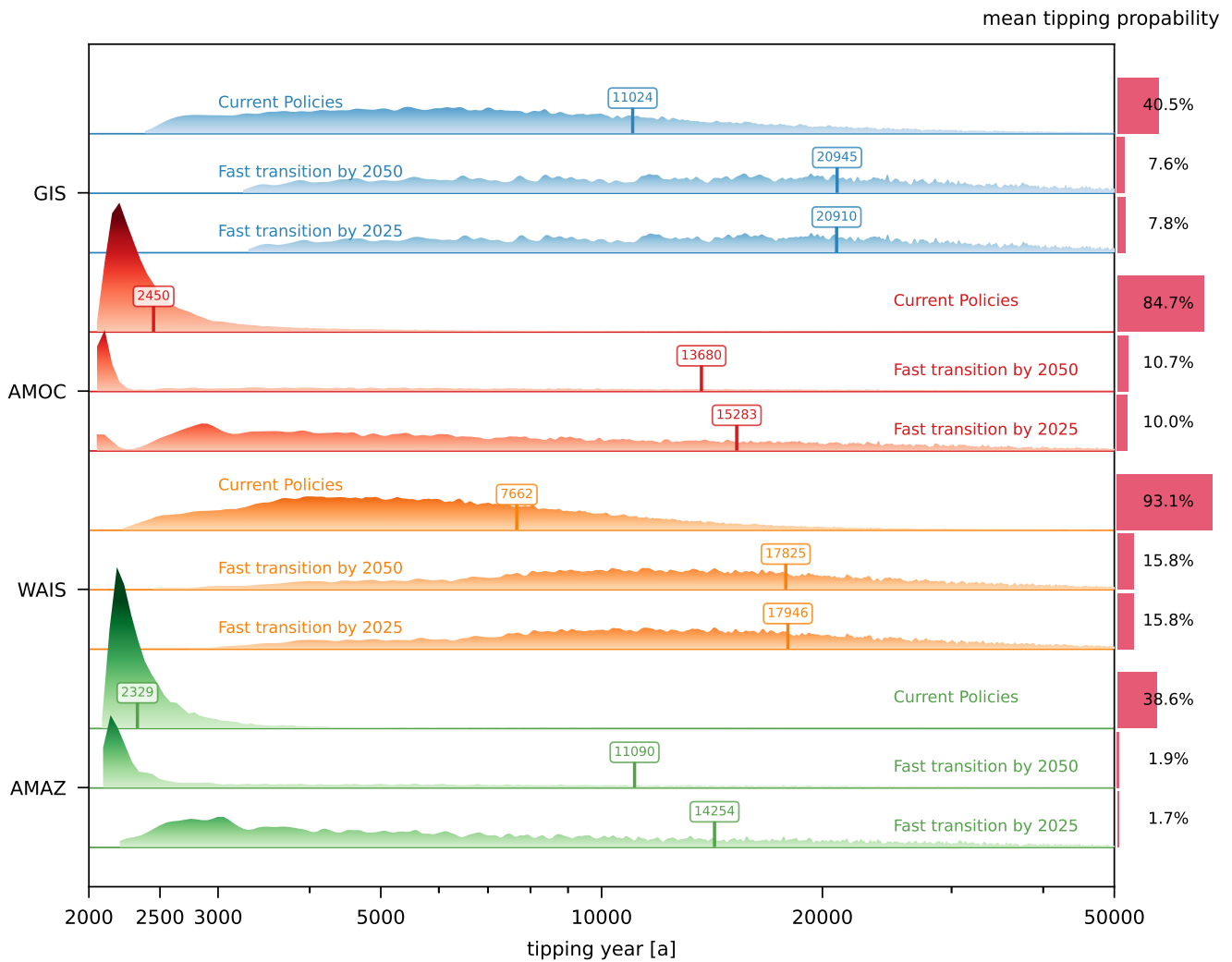


Figure 5: **Effect of fast energy transition delay on tipping time.** Probability distribution of tipping events over time for the four tipping elements and selected fast transition scenarios returning to $T_{\text{conv}}=1.0^{\circ}\text{C}$ and under Current Policies ($T_{\text{conv}}=2.7^{\circ}\text{C}$). Vertical lines with boxes show the median tipping year of the respective scenario. The bars on the right show the mean long-term (after 50,000 years) probability for tipping the respective element associated with each scenario.

withstand an extreme loss event expected to occur, on average, once every 200 years, corresponding to an annual failure probability of 0.5%.⁵⁹ If this threshold is taken as the maximum tolerable probability of triggering climate tipping, peak warming would need to remain below 2.0°C and decline thereafter to a long-term convergence temperature below 0.8°C (Fig. 6a, light green area; see also the pathway in Fig. 6d).

Although this is as good as we can hope to achieve, a risk level of 0.5% is deemed unacceptable in many other societal situations where the precautionary principle is applied (e.g. aviation, nuclear power plant safety, civil engineering, health).⁶⁰ Increasing the tolerated level of tipping probability, for example, a mean long-term tipping probability of 10%, temperature would need to return to around 1.0°C (such as the pathway in Fig. 6c). By contrast, starting a fast transition in 2100 (peak warming below 3.0°C) and returning to 1.5°C after 2200 would cause about a 50% tipping probability (Fig. 6a and b).

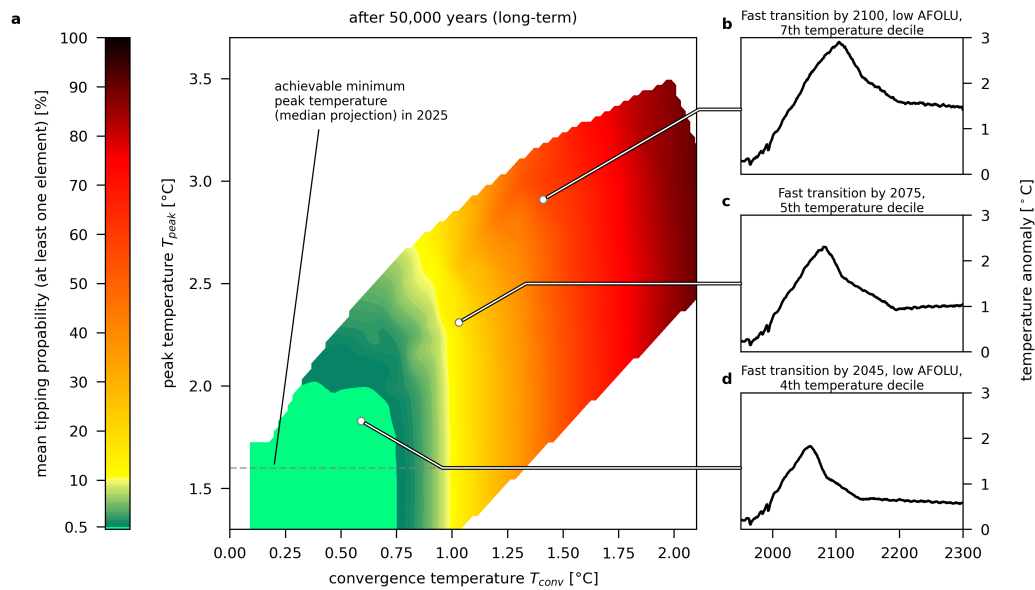


Figure 6: **A safe operating space for mitigation pathways.** **a**, Long-term (after 50,000 years) mean tipping probability as a function peak and convergence temperatures of pathways. The underlying number of data points is 493. The underlying pathways are characterized by a mean temperature overshoot duration of less than 220 Ka (Kelvin-years; mean temperature exceedance above convergence temperature multiplied by overshoot duration). For pathways converging to well below 1.0°C, we tested additional 'very low' AFOLU emission scenarios (Supplementary Fig. 1). **b**, Temperature timeseries of a fast energy transition starting in 2100 with low AFOLU emissions (7th temperature decile). **c**, Temperature timeseries of a fast energy transition starting in 2075 with base AFOLU emissions (5th temperature decile). **d**, Temperature timeseries of a fast energy transition starting in 2045 with low AFOLU emissions (4th temperature decile).

4 Discussion

Our results show that highly ambitious, technically feasible fast energy transitions can substantially reduce climate tipping probabilities relative to emissions following a Current Policies scenario. Earlier transitions may lower the probability of tipping and postpone potential tipping events by hundreds of years. Fast energy transitions thereby provide more time for communities to adapt even if tipping may occur.^{61,62} This additional time is particularly relevant for exposed regions—such as Iceland, which already acknowledges AMOC tipping as a threat to national security.⁶³ The additional adaption time might be used to increase the resilience of the tipping element (e.g. afforestation in the Amazon), install monitoring systems, or develop anticipatory and flexible adaptation portfolios tailored to Earth-system tipping elements.⁶² Such portfolios may need to extend beyond current adaptation measures (e.g. drought, wildfire, and flood protection⁶⁴) to include avoiding development lock-ins in exposed areas, planned retreat, and ecosystem restoration.

Tipping probabilities increase with every 0.1°C increase of peak heating (e.g. by 0.5 percentage points for the AMOC in the short-term) and every 0.1°C increase of convergence temperature (e.g. by 6.5 percentage points for the WAIS in the long-term, Supplementary Fig. 9). Yet, our results suggest that it might still be possible to reduce long-term tipping probabilities to below 0.5%. This would require limiting peak heating to 2.0°C and returning to 0.8°C as soon as possible thereafter. While this underscores the main consensus of the Paris Agreement—limiting global heating to below 2.0°C⁵⁷—, it further highlights that returning to 1.5°C is likely insufficient under precautionary considerations. Instead, in addition to the Paris Agreement, aiming at convergence temperatures of 1.0°C or below would be required, also because some tipping threshold uncertainties are as low as about 1.0°C of global warming (e.g. for the West Antarctic Ice Sheet). This finding supports previous emphasis on establishing 1.0°C as the long-term safe temperature goal.^{54–56}

Returning to 1.0°C requires large-scale deployment of CDR,^{39,65} which would divert resources from other societal priorities. For example, delaying the fast transition from 2030 to 2035 increases the required electricity investments in CDR for returning to 1.0°C by 182 TWh (Supplementary Figure 10; equivalent to 50 years of current electricity generation). Besides the additional energy demand, significantly higher financial investments into CDR would

be needed (around 35 trillion United States Dollars (USD) when operating DACCS at 200 USD per ton CO₂,⁶⁶ Supplementary Fig. 10). Further, the CDR needed to bring temperatures back to 1.0°C would exceed the limited geological storage capacity for CO₂ (1,460 Gt CO₂, uncertainty: 1,290–2,710 Gt CO₂)⁶⁷ in the period 2027–2065 (Supplementary Fig. 11) when following Current Policies. Consequently, starting fast transitions after 2027 would with increasing likelihood need to rely on potentially more costly carbon storage options, for example, converting captured CO₂ into solid carbon with subsequent storage in e.g. concrete.^{68,69}

Other CDR options exist beyond DACCS. These options comprise BECCS, afforestation and reforestation, ocean fertilization, ocean alkalinity enhancement, or enhanced weathering. However, their aggregated technical potential is limited and highly uncertain (5–236 Gt CO₂ a⁻¹)¹³⁶. When accounting for environmental constraints—e.g. impacts on water and air quality, land use, toxic trace-metal mobilization, marine ecosystem disruption, and the risk of ocean anoxia—feasible deployment may even be substantially lower (to 3.6–20.1 Gt CO₂ a⁻¹,⁶⁵ when omitting ocean-based CDR technologies due to their uncertain feasibility³⁶). Moreover, much of this limited CDR potential may be needed to compensate residual hard-to-abate emissions (e.g. from buildings, aviation and shipping, industry; 4.7–9.0 Gt CO₂ a⁻¹ by 2060⁷⁰). In our work, we model neither these residual emissions nor CDR technologies other than DACCS, as we assume them to be balanced. For instance, we also exclude BECCS, a commonly modeled CDR options,³⁶ because its estimated potential is limited (below 5 Gt CO₂ a⁻¹ when biodiversity constraints are considered⁶⁵) and small relative to the DACCS removal rates in our model (reaching peak values of 64–75 Gt CO₂ a⁻¹ across scenarios aiming at 1.0°C).

Consequently, if the potential of other CDR methods (e.g. BECCS) would be larger than residual emissions, temperatures could decline faster than modeled here. Faster carbon removal would then lead to shorter overshoot durations, which likely reduces the short-term tipping probabilities of fast-moving tipping elements (AMOC, AMAZ). In contrast, if other CDR options fall short of compensating hard-to-abate emissions, returning to safe levels of CO₂ concentration would be delayed.^{39,70,71} Negative emissions therefore need to be reframed from a means to compensate residual emissions to an essential way to return to a low-risk climate state.

The chemical sector illustrates the importance of minimizing residual emissions. Because carbon-containing feedstocks remain indispensable, residual emissions are expected to persist even under ambitious transition pathways.^{72–74} Deeper electrification, enhanced carbon circularity, and substitution of fossil feedstocks with sustainable carbon sources⁷⁵ could therefore reduce the burden placed on CDR. These strategies may also align with current geopolitical and strategic-autonomy objectives⁷⁶ aimed at lowering dependence on fossil carbon. More broadly, these developments are further reinforced by the improving competitiveness of non-fossil technologies, including renewable electricity⁷⁷ and electric vehicles,⁷⁸ which suggests that defossilization may proceed even beyond strategic or climate-mitigation imperatives.

Our analysis has several limitations beyond the exclusion of CDR options other than DACCS. First, the 3-Machine model is a simplified representation of the global energy system. Unlike commonly used IAMs, it does not resolve individual sectors or energy sub-technologies. Nevertheless, despite this simplified structure, the fast energy transition pathways investigated here yield temperature trajectories and tipping probabilities that are close to those of other highly ambitious IAM pathways, such as Shared Socioeconomic Pathway 1 (SSP1; Supplementary Fig. 12). Yet, the 3-machines model allows modeling highly ambitious and physically consistent scenarios beyond 2100 based on the fundamental feedback of energy.

Second, PyCascades describes tipping elements phenomenologically through nonlinear differential equations which, although well-substantiated,^{5,79} remain significant simplifications. We also omit several nonlinear components and potential climate tipping elements (e.g. monsoon systems, boreal forests, permafrost), focusing instead on four core elements decisive for the planetary state. This choice deliberately restricts the scope to elements whose structure and interactions are best understood.^{5,79} Furthermore, we do not explicitly model the carbon and temperature feedback of tipping (e.g., carbon release from Amazon dieback); however, i) we do model direct interactions between tipping elements (Fig. 2), and ii) we remain conservative, as the global temperature impact of these feedbacks is likely positive but remains uncertain in absolute magnitude.^{32,80,81} Furthermore, we likely overestimate the uncertainty in tipping probability, because we conservatively sample uniformly across the full elicited ranges of critical temperatures and tipping timescales.

In the future, advancing the knowledge of tipping points and their interactions will enable incorporation of a wider range of non-linear Earth system dynamics in PyCascades. Furthermore, future studies should expand on the set of CDR technologies considered and introduce additional possible constraints to the 3-Machine model, such as the material-energy feedback.⁴⁰ Yet, overall, we expect our central conclusion—that ambitious mitigation pathways can substantially reduce non-linear risks in the climate system relative to Current Policies—to remain robust despite the uncertainties and limitations of our approach.

Author contributions H.S., H.D., G.G.G, and N.W. designed the study. H.S. curated the data, carried out the modeling, created the figures, and wrote the first draft of the manuscript. H.S., H.D., G.G.G, and N.W. performed the analysis and contributed to editing and reviewing the manuscript.

Declaration of interest The authors declare no competing interests.

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5 Data availability

The data used to produce the outputs presented in this paper can be accessed via Zenodo under accession code 20426450: <https://doi.org/10.5281/zenodo.20426449>. The emission pathways are outputs of the 3-Machine Energy Transition model, which is accessible under <https://doi.org/10.5281/zenodo.20426449>. The current policy scenario outputs are taken from the AR6 Scenario Explorer and Database (<https://data.ece.iiasa.ac.at/ar6/>).

6 Code availability

A code to reproduce the results is available at a Zenodo repository under accession code 20426450: <https://doi.org/10.5281/zenodo.20426449>.

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