Trajectories of the Earth System in the Anthropocene

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Abstract

We explore the risk that self-reinforcing feedbacks could push the Earth System toward a planetary threshold that, if crossed, could prevent stabilization of the climate at intermediate temperature rises and cause continued warming on a “Hothouse Earth” pathway even as human emissions are reduced. Crossing the threshold would lead to a much higher global average temperature than any interglacial in the past 1.2 million years and to sea levels significantly higher than at any time in the Holocene. We examine the evidence that such a threshold might exist and where it might be. If the threshold is crossed, the resulting trajectory would likely cause serious disruptions to ecosystems, society, and economies. Collective human action is required to steer the Earth System away from a potential threshold and stabilize it in a habitable interglacial-like state. Such action entails

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stewardship of the entire Earth System—biosphere, climate, and societies—and could include decarbonization of the global economy, enhancement of biosphere carbon sinks, behavioral changes, technological innovations, new governance arrangements, and transformed social values.

Earth System trajectories climate change Anthropocene biosphere feedbacks tipping elements

The Anthropocene is a proposed new geological epoch (**1**) based on the observation that human impacts on essential planetary processes have become so profound (**2**) that they have driven the Earth out of the Holocene epoch in which agriculture, sedentary communities, and eventually, socially and technologically complex human societies developed. The formalization of the Anthropocene as a new geological epoch is being considered by the stratigraphic community (**3**), but regardless of the outcome of that process, it is becoming apparent that Anthropocene conditions transgress Holocene conditions in several respects (**2**). The knowledge that human activity now rivals geological forces in influencing the trajectory of the Earth System has important implications for both Earth System science and societal decision making. While recognizing that different societies around the world have contributed differently and unequally to pressures on the Earth System and will have varied capabilities to alter future trajectories (**4**), the sum total of human impacts on the system needs to be taken into account for analyzing future trajectories of the Earth System.

Here, we explore potential future trajectories of the Earth System by addressing the following questions.

> Is there a planetary threshold in the trajectory of the Earth System that, if crossed, could prevent stabilization in a range of intermediate temperature rises?
>
> Given our understanding of geophysical and biosphere feedbacks intrinsic to the Earth System, where might such a threshold be?
>
> If a threshold is crossed, what are the implications, especially for the wellbeing of human societies?
>
> What human actions could create a pathway that would steer the Earth System away from the potential threshold and toward the maintenance of interglacial-like conditions?

Addressing these questions requires a deep integration of knowledge from biogeophysical Earth System science with that from the social sciences and humanities on the development and functioning of human societies (**5**). Integrating the requisite knowledge can be difficult, especially in light of the formidable range of timescales

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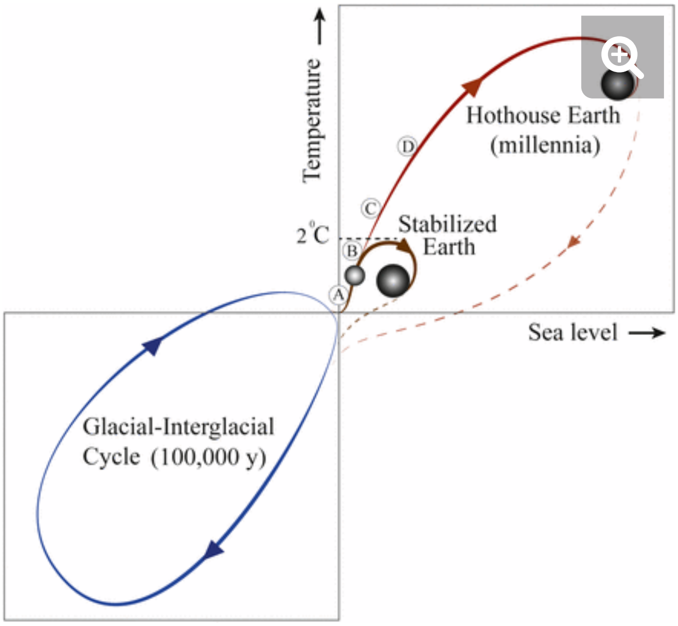
involved. Increasingly, concepts from complex systems analysis provide a framework that unites the diverse fields of inquiry relevant to the Anthropocene (**6**). Earth System dynamics can be described, studied, and understood in terms of trajectories between alternate states separated by thresholds that are controlled by nonlinear processes, interactions, and feedbacks. Based on this framework, we argue that social and technological trends and decisions occurring over the next decade or two could significantly influence the trajectory of the Earth System for tens to hundreds of thousands of years and potentially lead to conditions that resemble planetary states that were last seen several millions of years ago, conditions that would be inhospitable to current human societies and to many other contemporary species.

Risk of a Hothouse Earth Pathway

Limit Cycles and Planetary Thresholds.

The trajectory of the Earth System through the Late Quaternary, particularly the Holocene, provides the context for exploring the human-driven changes of the Anthropocene and the future trajectories of the system (*SI Appendix* has more detail). **Fig. 1** shows a simplified representation of complex Earth System dynamics, where the physical climate system is subjected to the effects of slow changes in Earth's orbit and inclination. Over the Late Quaternary (past 1.2 million years), the system has remained bounded between glacial and interglacial extremes. Not every glacial–interglacial cycle of the past million years follows precisely the same trajectory (**7**), but the cycles follow the same overall pathway (a term that we use to refer to a family of broadly similar trajectories). The full glacial and interglacial states and the ca. 100,000-years oscillations between them in the Late Quaternary loosely constitute limit cycles (technically, the asymptotic dynamics of ice ages are best modeled as pullback attractors in a nonautonomous dynamical system). This limit cycle is shown in a schematic fashion in blue in **Fig. 1**, *Lower Left* using temperature and sea level as the axes. The Holocene is represented by the top of the limit cycle loop near the label A.



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A schematic illustration of possible future pathways of the climate against the background of the typical glacial–interglacial cycles (*Lower Left*). The interglacial state of the Earth System is at the top of the glacial–interglacial cycle, while the glacial state is at the bottom. Sea level follows temperature change relatively slowly through thermal expansion and the melting of glaciers and ice caps. The horizontal line in the middle of the figure represents the preindustrial temperature level, and the current position of the Earth System is shown by the small sphere on the red line close to the divergence between the Stabilized Earth and Hothouse Earth pathways. The proposed planetary threshold at ~2 °C above the preindustrial level is also shown. The letters along the Stabilized Earth/Hothouse Earth pathways represent four time periods in Earth's recent past that may give insights into positions along these pathways (*SI Appendix*): A, Mid-Holocene; B, Eemian; C, Mid-Pliocene; and D, Mid-Miocene. Their positions on the pathway are approximate only. Their temperature ranges relative to preindustrial are given in *SI Appendix*, Table S1.

The current position of the Earth System in the Anthropocene is shown in **Fig. 1**, *Upper Right* by the small ball on the pathway that leads away from the glacial–interglacial limit cycle. In **Fig. 2**, a stability landscape, the current position of the Earth System is represented by the globe at the end of the solid arrow in the deepening Anthropocene basin of attraction.

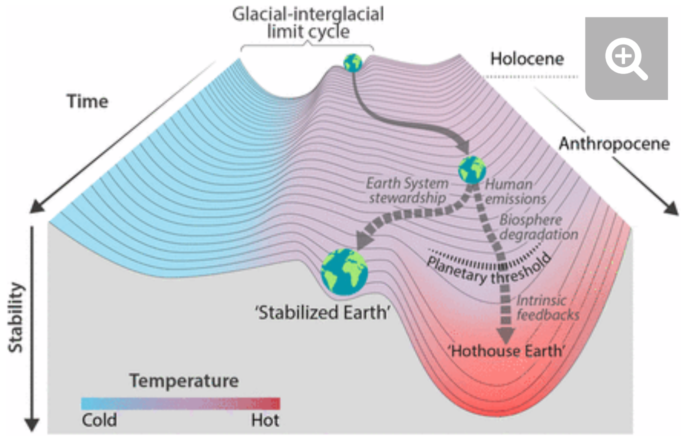

Fig. 2. **Download figure** | **Open in new tab** | **Download powerpoint**

Stability landscape showing the pathway of the Earth System out of the Holocene and thus, out of the glacial–interglacial limit cycle to its present position in the hotter Anthropocene. The fork in the road in **Fig. 1** is shown here as the two divergent pathways of the Earth System in the future (broken arrows). Currently, the Earth System is on a Hothouse Earth pathway driven by human emissions of greenhouse gases and biosphere degradation toward a planetary threshold at ~2 °C (horizontal broken line at 2 °C in **Fig. 1**), beyond which the system follows an essentially irreversible pathway driven by intrinsic biogeophysical feedbacks. The other pathway leads to Stabilized Earth, a pathway of Earth System stewardship guided by human-created feedbacks to a quasistable, human-maintained basin of attraction. "Stability" (vertical axis) is defined here as the inverse of the potential energy of the system. Systems in a highly stable state (deep valley) have low potential energy, and considerable energy is required to move them out of this stable state. Systems in an unstable state (top of a hill) have high potential energy, and they require only a little additional energy to push them off the hill and down toward a valley of lower potential energy.

The Anthropocene represents the beginning of a very rapid human-driven trajectory of the Earth System away from the glacial–interglacial limit cycle toward new, hotter climatic conditions and a profoundly different biosphere (**2**, **8**, **9**) (*SI Appendix*). The current position, at over 1 °C above a preindustrial baseline (**10**), is nearing the upper envelope of interglacial conditions over the past 1.2 million years (*SI Appendix*, Table S1). More importantly, the rapid trajectory of the climate system over the past half-century along with technological lock in and socioeconomic inertia in human systems commit the climate system to conditions beyond the envelope of past interglacial conditions. We, therefore, suggest that the Earth System may already have passed one "fork in the road" of potential pathways, a bifurcation (near A in **Fig. 1**) taking the Earth System out of the next glaciation cycle (**11**).

In the future, the Earth System could potentially follow many trajectories (**12**, **13**), often represented by the large range of global temperature rises simulated by climate models (**14**). In most analyses, these trajectories are largely driven by the amount of greenhouse gases that human activities have already emitted and will continue to emit into the atmosphere over the rest of this century and beyond—with a presumed quasilinear relationship between cumulative carbon dioxide emissions and global temperature rise (**14**). However, here we suggest that biogeophysical feedback processes within the Earth System coupled with direct human degradation of the biosphere may play a more important role than normally assumed, limiting the range of potential future trajectories and potentially eliminating the possibility of the intermediate trajectories. We argue that there is a significant risk that these internal dynamics, especially strong nonlinearities in feedback processes, could become an important or perhaps, even dominant factor in steering the trajectory that the Earth System actually follows over coming centuries.

This risk is represented in **Figs. 1** and **2** by a planetary threshold (horizontal broken line in **Fig. 1** on the Hothouse Earth pathway around 2 °C above preindustrial temperature). Beyond this threshold, intrinsic biogeophysical feedbacks in the Earth System (***Biogeophysical Feedbacks***) could become the dominant processes controlling the system's trajectory. Precisely where a potential planetary threshold might be is uncertain (**15**, **16**). We suggest 2 °C because of the risk that a 2 °C warming could activate important tipping elements (**12**, **17**), raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (***Tipping Cascades***). Such cascades comprise, in essence, the dynamical process that leads to thresholds in complex systems (section 4.2 in ref. **18**).

This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a "Hothouse Earth" pathway. The challenge that humanity faces is to create a "Stabilized Earth" pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (**Fig. 2**). The human-created Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System's stability landscape without human stewardship to create and maintain it. Creating such a pathway and basin of attraction requires a fundamental change in the role of humans on the planet. This stewardship role requires deliberate and sustained action to become an integral, adaptive part of Earth System dynamics, creating feedbacks that keep the system on a Stabilized Earth pathway (***Alternative Stabilized Earth Pathway***).

We now explore this critical question in more detail by considering the relevant biogeophysical feedbacks (***Biogeophysical Feedbacks***) and the risk of tipping cascades (***Tipping Cascades***).

Biogeophysical Feedbacks.

The trajectory of the Earth System is influenced by biogeophysical feedbacks within the system that can maintain it in a given state (negative feedbacks) and those that can amplify a perturbation and drive a transition to a different state (positive feedbacks). Some of the key negative feedbacks that could maintain the Earth System in Holocene-like conditions—notably, carbon uptake by land and ocean systems—are weakening relative to human forcing (**19**), increasing the risk that positive feedbacks could play an important role in determining the Earth System's trajectory. **Table 1** summarizes carbon cycle feedbacks that could accelerate warming, while *SI Appendix*, Table S2 describes in detail a more complete set of biogeophysical feedbacks that can be triggered by forcing levels likely to be reached within the rest of the century.

Table 1. **VIEW INLINE** | **VIEW POPUP**

Carbon cycle feedbacks in the Earth System that could accelerate global warming

Most of the feedbacks can show both continuous responses and tipping point behavior in which the feedback process becomes self-perpetuating after a critical threshold is crossed; subsystems exhibiting this behavior are often called "tipping elements" (**17**). The type of behavior—continuous response or tipping point/abrupt change—can depend on the magnitude or the rate of forcing, or both. Many feedbacks will show some gradual change before the tipping point is reached.

A few of the changes associated with the feedbacks are reversible on short timeframes of 50–100 years (e.g., change in Arctic sea ice extent with a warming or cooling of the climate; Antarctic sea ice may be less reversible because of heat accumulation in the Southern Ocean), but most changes are largely irreversible on timeframes that matter to contemporary societies (e.g., loss of permafrost carbon). A few of the feedbacks do not have apparent thresholds (e.g., change in the land and ocean physiological carbon sinks, such as increasing carbon uptake due to the CO_2 fertilization effect or decreasing uptake due to a decrease in rainfall). For some of the tipping elements, crossing the tipping point could trigger an abrupt, nonlinear response (e.g., conversion of large areas of the Amazon rainforest to a savanna or seasonally dry forest), while for others, crossing the tipping point would lead to a more gradual but self-perpetuating response (large-scale loss of permafrost). There could also be considerable lags after the crossing of a threshold, particularly for those tipping elements that involve the melting of large masses of ice. However, in some cases, ice loss can be very rapid when occurring as massive iceberg outbreaks (e.g., Heinrich Events).

For some feedback processes, the magnitude—and even the direction—depend on the rate of climate change. If the rate of climate change is small, the shift in biomes can track the change in temperature/moisture, and the biomes may shift gradually, potentially taking up carbon from the atmosphere as the climate warms and atmospheric CO_2 concentration increases. However, if the rate of climate change is too large or too fast, a tipping point can be crossed, and a rapid biome shift may occur via extensive disturbances (e.g., wildfires, insect attacks, droughts) that can abruptly remove an existing biome. In some terrestrial cases, such as widespread wildfires, there could be a pulse of carbon to the atmosphere, which if large enough, could influence the trajectory of the Earth System (**29**).

Varying response rates to a changing climate could lead to complex biosphere dynamics with implications for feedback processes. For example, delays in permafrost thawing would most likely delay the projected northward migration of boreal forests (**30**), while warming of the southern areas of these forests could result in their conversion to steppe grasslands of significantly lower carbon storage capacity. The overall result would be a positive feedback to the climate system.

The so-called "greening" of the planet, caused by enhanced plant growth due to increasing atmospheric CO_2 concentration (**31**), has increased the land carbon sink in recent decades (**32**). However, increasing atmospheric CO_2 raises temperature, and hotter leaves photosynthesize less well. Other feedbacks are also involved—for instance, warming the soil increases microbial respiration, releasing CO_2 back into the atmosphere.

Our analysis focuses on the strength of the feedback between now and 2100. However, several of the feedbacks that show negligible or very small magnitude by 2100 could nevertheless be triggered well before then, and they could eventually generate significant feedback strength over longer timeframes—centuries and even millennia—and thus, influence the long-term trajectory of the Earth System. These feedback processes include permafrost thawing, decomposition of ocean methane hydrates, increased marine bacterial respiration, and loss of polar ice sheets accompanied by a rise in sea levels and potential amplification of temperature rise through changes in ocean circulation (**33**).

Tipping Cascades.

Fig. 3 shows a global map of some potential tipping cascades. The tipping elements fall into three clusters based on their estimated threshold temperature (**12**, **17**, **39**). Cascades could be formed when a rise in global temperature reaches the level of the lower-temperature cluster, activating tipping elements, such as loss of the Greenland Ice Sheet or Arctic sea ice. These tipping elements, along with some of the nontipping element feedbacks (e.g., gradual weakening of land and ocean physiological carbon sinks), could push the global average temperature even higher, inducing tipping in mid- and higher-temperature clusters. For example, tipping (loss) of the Greenland Ice Sheet could trigger a critical transition in the Atlantic Meridional

Ocean Circulation (AMOC), which could together, by causing sea-level rise and Southern Ocean heat accumulation, accelerate ice loss from the East Antarctic Ice Sheet (**32**, **40**) on timescales of centuries (**41**).

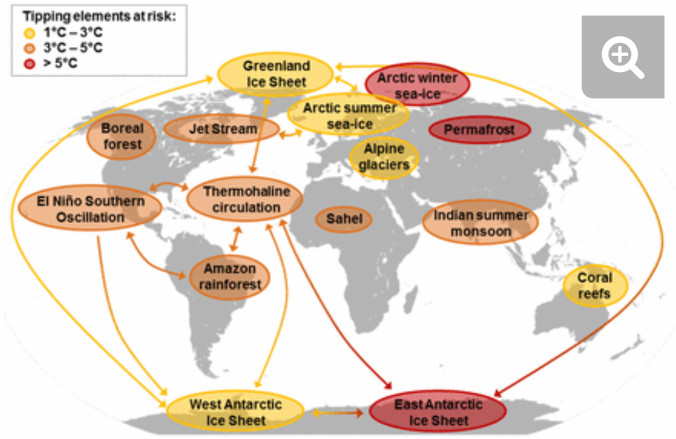

Fig. 3. **Download figure** | **Open in new tab** | **Download powerpoint**

Global map of potential tipping cascades. The individual tipping elements are color- coded according to estimated thresholds in global average surface temperature (tipping points) (**12**, **34**). Arrows show the potential interactions among the tipping elements based on expert elicitation that could generate cascades. Note that, although the risk for tipping (loss of) the East Antarctic Ice Sheet is proposed at >5 °C, some marine-based sectors in East Antarctica may be vulnerable at lower temperatures (**35**⇓⇓–**38**).

Observations of past behavior support an important contribution of changes in ocean circulation to such feedback cascades. During previous glaciations, the climate system flickered between two states that seem to reflect changes in convective activity in the Nordic seas and changes in the activity of the AMOC. These variations caused typical temperature response patterns called the “bipolar seesaw” (**42**⇓–**44**). During extremely cold conditions in the north, heat accumulated in the Southern Ocean, and Antarctica warmed. Eventually, the heat made its way north and generated subsurface warming that may have been instrumental in destabilizing the edges of the Northern Hemisphere ice sheets (**45**).

If Greenland and the West Antarctic Ice Sheet melt in the future, the freshening and cooling of nearby surface waters will have significant effects on the ocean circulation. While the probability of significant circulation changes is difficult to quantify, climate model simulations suggest that freshwater inputs compatible with current rates of Greenland melting are sufficient to have measurable effects on ocean temperature and circulation (**46**, **47**). Sustained warming of the northern high latitudes as a result of this process could accelerate feedbacks or activate tipping elements in that region, such as permafrost degradation, loss of Arctic sea ice, and boreal forest dieback.

While this may seem to be an extreme scenario, it illustrates that a warming into the range of even the lower-temperature cluster (i.e., the Paris targets) could lead to tipping in the mid- and higher-temperature clusters via cascade effects. Based on this analysis of tipping cascades and taking a risk-averse approach, we suggest that a potential planetary threshold could occur at a temperature rise as low as ~2.0 °C above preindustrial (**Fig. 1**).

Alternative Stabilized Earth Pathway

If the world's societies want to avoid crossing a potential threshold that locks the Earth System into the Hothouse Earth pathway, then it is critical that they make deliberate decisions to avoid this risk and maintain the Earth System in Holocene-like conditions. This human-created pathway is represented in **Figs. 1** and **2** by what we call Stabilized Earth (small loop at the bottom of **Fig. 1**, *Upper Right*), in which the Earth System is maintained in a state with a temperature rise no greater than 2 °C above preindustrial (a "super-Holocene" state) (**11**). Stabilized Earth would require deep cuts in greenhouse gas emissions, protection and enhancement of biosphere carbon sinks, efforts to remove CO_2 from the atmosphere, possibly solar radiation management, and adaptation to unavoidable impacts of the warming already occurring (**48**). The short broken red line beyond Stabilized Earth in **Fig. 1**, *Upper Right* represents a potential return to interglacial-like conditions in the longer term.

In essence, the Stabilized Earth pathway could be conceptualized as a regime of the Earth System in which humanity plays an active planetary stewardship role in maintaining a state intermediate between the glacial–interglacial limit cycle of the Late Quaternary and a Hothouse Earth (**Fig. 2**). We emphasize that Stabilized Earth is not an intrinsic state of the Earth System but rather, one in which humanity commits to a pathway of ongoing management of its relationship with the rest of the Earth System.

A critical issue is that, if a planetary threshold is crossed toward the Hothouse Earth pathway, accessing the Stabilized Earth pathway would become very difficult no matter what actions human societies might take. Beyond the threshold, positive (reinforcing) feedbacks within the Earth System—outside of human influence or control—could become the dominant driver of the system's pathway, as individual tipping elements create linked cascades through time and with rising temperature (**Fig. 3**). In other words, after the Earth System is committed to the Hothouse Earth pathway, the alternative Stabilized Earth pathway would very likely become inaccessible as illustrated in **Fig. 2**.

What Is at Stake?

Hothouse Earth is likely to be uncontrollable and dangerous to many, particularly if we transition into it in only a century or two, and it poses severe risks for health, economies, political stability (**12**, **39**, **49**, **50**) (especially for the most climate vulnerable), and ultimately, the habitability of the planet for humans.

Insights into the risks posed by the rapid climatic changes emerging in the Anthropocene can be obtained not only from contemporary observations (**51**⇓⇓⇓–**55**) but also, from interactions in the past between human societies and regional and seasonal hydroclimate variability. This variability was often much more pronounced than global, longer-term Holocene variability (*SI Appendix*). Agricultural production and water supplies are especially vulnerable to changes in the hydroclimate, leading to hot/dry or cool/wet extremes. Societal declines, collapses, migrations/resettlements, reorganizations, and cultural changes were often associated with severe regional droughts and with the global megadrought at 4.2–3.9 thousand years before present, all occurring within the relative stability of the narrow global Holocene temperature range of approximately ±1 °C (**56**).

SI Appendix, Table S4 summarizes biomes and regional biosphere–physical climate subsystems critical for human wellbeing and the resultant risks if the Earth System follows a Hothouse Earth pathway. While most of these biomes or regional systems may be retained in a Stabilized Earth pathway, most or all of them would likely be substantially changed or degraded in a Hothouse Earth pathway, with serious challenges for the viability of human societies.

For example, agricultural systems are particularly vulnerable, because they are spatially organized around the relatively stable Holocene patterns of terrestrial primary productivity, which depend on a well-established and predictable spatial distribution of temperature and precipitation in relation to the location of fertile soils as well as on a particular atmospheric CO_2 concentration. Current understanding suggests that, while a Stabilized Earth pathway could result in an approximate balance between increases and decreases in regional production as human systems adapt, a Hothouse Earth trajectory will likely exceed the limits of adaptation and result in a substantial overall decrease in agricultural production, increased prices, and even more disparity between wealthy and poor countries (**57**).

The world's coastal zones, especially low-lying deltas and the adjacent coastal seas and ecosystems, are particularly important for human wellbeing. These areas are home to much of the world's population, most of the emerging megacities, and a significant amount of infrastructure vital for both national economies and international trade. A Hothouse Earth trajectory would almost certainly flood deltaic environments, increase the risk of damage from coastal storms, and eliminate coral reefs (and all of the benefits that they provide for societies) by the end of this century or earlier (**58**).

Human Feedbacks in the Earth System.

In the dominant climate change narrative, humans are an external force driving change to the Earth System in a largely linear, deterministic way; the higher the forcing in terms of anthropogenic greenhouse gas emissions, the higher the global average temperature. However, our analysis argues that human societies and our activities need to be recast as an integral, interacting component of a complex, adaptive Earth System. This framing puts the focus not only on human system dynamics that reduce greenhouse gas emissions but also, on those that create or enhance negative feedbacks that reduce the risk that the Earth System will cross a planetary threshold and lock into a Hothouse Earth pathway.

Humanity's challenge then is to influence the dynamical properties of the Earth System in such a way that the emerging unstable conditions in the zone between the Holocene and a very hot state become a de facto stable intermediate state (Stabilized Earth) (**Fig. 2**). This requires that humans take deliberate, integral, and adaptive steps to reduce dangerous impacts on the Earth System, effectively monitoring and changing behavior to form feedback loops that stabilize this intermediate state.

There is much uncertainty and debate about how this can be done—technically, ethically, equitably, and economically—and there is no doubt that the normative, policy, and institutional aspects are highly challenging. However, societies could take a wide range of actions that constitute negative feedbacks, summarized in *SI Appendix*, Table S5, to steer the Earth System toward Stabilized Earth. Some of these actions are already altering emission trajectories. The negative feedback actions fall into three broad categories: (*i*) reducing greenhouse gas emissions, (*ii*) enhancing or creating carbon sinks (e.g., protecting and enhancing biosphere carbon sinks and creating new types of sinks) (**59**), and (*iii*) modifying Earth's energy balance (for example, via solar radiation management, although that particular feedback entails very large risks of destabilization or degradation of several key processes in the Earth System) (**60**, **61**). While reducing emissions is a priority, much more could be done to reduce direct human pressures on critical biomes that contribute to the regulation of the state of the Earth System through carbon sinks and moisture feedbacks, such as the Amazon and boreal forests (**Table 1**), and to build much more effective stewardship of the marine and terrestrial biospheres in general.

The present dominant socioeconomic system, however, is based on high-carbon economic growth and exploitative resource use (**9**). Attempts to modify this system have met with some success locally but little success globally in reducing greenhouse gas emissions or building more effective stewardship of the biosphere. Incremental linear changes to the present socioeconomic system are not enough to stabilize the Earth System. Widespread, rapid, and fundamental transformations will likely be required to reduce the risk of crossing the threshold and locking in the Hothouse Earth pathway; these include changes in behavior, technology and innovation, governance, and values (**48**, **62**, **63**).

International efforts to reduce human impacts on the Earth System while improving wellbeing include the United Nations Sustainable Development Goals and the commitment in the Paris agreement to keep warming below 2 °C. These international governance initiatives are matched by carbon reduction commitments by countries, cities, businesses, and individuals (**64**⇓–**66**) , but as yet, these are not enough to meet the Paris target. Enhanced ambition will need new collectively shared values, principles, and frameworks as well as education to support such changes (**67**, **68**). In essence, effective Earth System stewardship is an essential precondition for the prosperous development of human societies in a Stabilized Earth pathway (**69**, **70**).

In addition to institutional and social innovation at the global governance level, changes in demographics, consumption, behavior, attitudes, education, institutions, and socially embedded technologies are all important to maximize the chances of achieving a Stabilized Earth pathway (**71**). Many of the needed shifts may take decades to have a globally aggregated impact (*SI Appendix*, Table S5), but there are indications that society may be reaching some important societal tipping points. For example, there has been relatively rapid progress toward slowing or reversing population growth through declining fertility resulting from the empowerment of women, access to birth control technologies, expansion of educational opportunities, and rising income levels (**72**, **73**). These demographic changes must be complemented by sustainable per capita consumption patterns, especially among the higher per capita consumers. Some changes in consumer behavior have been observed (**74**, **75**), and opportunities for consequent major transitions in social norms over broad scales may arise (**76**). Technological innovation is contributing to more rapid decarbonization and the possibility for removing CO_2 from the atmosphere (**48**).

Ultimately, the transformations necessary to achieve the Stabilized Earth pathway require a fundamental reorientation and restructuring of national and international institutions toward more effective governance at the Earth System level (**77**), with a much stronger emphasis on planetary concerns in economic governance, global trade, investments and finance, and technological development (**78**).

Building Resilience in a Rapidly Changing Earth System.

Even if a Stabilized Earth pathway is achieved, humanity will face a turbulent road of rapid and profound changes and uncertainties on route to it—politically, socially, and environmentally—that challenge the resilience of human societies (**79**⇓⇓–**82**). Stabilized Earth will likely be warmer than any other time over the last 800,000 years at least (**83**) (that is, warmer than at any other time in which fully modern humans have existed).

In addition, the Stabilized Earth trajectory will almost surely be characterized by the activation of some tipping elements (***Tipping Cascades*** and **Fig. 3**) and by nonlinear dynamics and abrupt shifts at the level of critical biomes that support humanity (*SI Appendix*, Table S4). Current rates of change of important features of the Earth System already match or exceed those of abrupt geophysical events in the past (*SI Appendix*). With these trends likely to continue for the next several decades at least, the contemporary way of guiding development founded on theories, tools, and beliefs of gradual or incremental change, with a focus on economy efficiency, will likely not be adequate to cope with this trajectory. Thus, in addition to adaptation, increasing resilience will become a key strategy for navigating the future.

Generic resilience-building strategies include developing insurance, buffers, redundancy, diversity, and other features of resilience that are critical for transforming human systems in the face of warming and possible surprise associated with tipping points (**84**). Features of such a strategy include (*i*) maintenance of diversity, modularity, and redundancy; (*ii*) management of connectivity, openness, slow variables, and feedbacks; (*iii*) understanding social–ecological systems as complex adaptive systems, especially at the level of the Earth System as a whole (**85**); (*iv*) encouraging learning and experimentation; and (*v*) broadening of participation and building of trust to promote polycentric governance systems (**86**, **87**).

Conclusions

Our systems approach, focusing on feedbacks, tipping points, and nonlinear dynamics, has addressed the four questions posed in the Introduction.

Our analysis suggests that the Earth System may be approaching a planetary threshold that could lock in a continuing rapid pathway toward much hotter conditions—Hothouse Earth. This pathway would be propelled by strong, intrinsic, biogeophysical feedbacks difficult to influence by human actions, a pathway that could not be reversed, steered, or substantially slowed.

Where such a threshold might be is uncertain, but it could be only decades ahead at a temperature rise of ~2.0 °C above preindustrial, and thus, it could be within the range of the Paris Accord temperature targets.

The impacts of a Hothouse Earth pathway on human societies would likely be massive, sometimes abrupt, and undoubtedly disruptive.

Avoiding this threshold by creating a Stabilized Earth pathway can only be achieved and maintained by a coordinated, deliberate effort by human societies to manage our relationship with the rest of the Earth System, recognizing that humanity is an integral, interacting component of the system. Humanity is now facing the need for critical decisions and actions that could influence our future for centuries, if not millennia (**88**).

How credible is this analysis? There is significant evidence from a number of sources that the risk of a planetary threshold and thus, the need to create a divergent pathway should be taken seriously:

First, the complex system behavior of the Earth System in the Late Quaternary is well-documented and understood. The two bounding states of the system—glacial and interglacial—are reasonably well-defined, the ca. 100,000-years periodicity of the limit cycle is established, and internal (carbon cycle and ice albedo feedbacks) and external (changes in insolation caused by changes in Earth's orbital parameters) driving processes are generally well-known. Furthermore, we know with high confidence that the progressive disintegration of ice sheets and the transgression of other tipping elements are difficult to reverse after critical levels of warming are reached.

Second, insights from Earth's recent geological past (*SI Appendix*) suggest that conditions consistent with the Hothouse Earth pathway are accessible with levels of atmospheric CO_2 concentration and temperature rise either already realized or projected for this century (*SI Appendix*, Table S1).

Third, the tipping elements and feedback processes that operated over Quaternary glacial–interglacial cycles are the same as several of those proposed as critical for the future trajectory of the Earth System (***Biogeophysical Feedbacks***, ***Tipping Cascades***, **Fig. 3**, **Table 1**, and *SI Appendix*, Table S2).

Fourth, contemporary observations (**29**, **38**) (*SI Appendix*) of tipping element behavior at an observed temperature anomaly of about 1 °C above preindustrial suggest that some of these elements are vulnerable to tipping within just a 1 °C to 3 °C increase in global temperature, with many more of them vulnerable at higher temperatures (***Biogeophysical Feedbacks*** and ***Tipping Cascades***) (**12**, **17**, **39**). This suggests that the risk of tipping cascades could be significant at a 2 °C temperature rise and could increase sharply beyond that point. We argue that a planetary threshold in the Earth System could exist at a temperature rise as low as 2 °C above preindustrial.

The Stabilized Earth trajectory requires deliberate management of humanity's relationship with the rest of the Earth System if the world is to avoid crossing a planetary threshold. We suggest that a deep transformation based on a fundamental reorientation of human values, equity, behavior, institutions, economies, and technologies is required. Even so, the pathway toward Stabilized Earth will involve considerable changes to the structure and functioning of the Earth System, suggesting that resilience-building strategies be given much higher priority than at present in decision making. Some signs are emerging that societies are initiating some of the necessary transformations. However, these transformations are still in initial stages, and the social/political tipping points that definitively move the current trajectory away from Hothouse Earth have not yet been crossed, while the door to the Stabilized Earth pathway may be rapidly closing.

Our initial analysis here needs to be underpinned by more in-depth, quantitative Earth System analysis and modeling studies to address three critical questions. (*i*) Is humanity at risk for pushing the system across a planetary threshold and irreversibly down a Hothouse Earth pathway? (*ii*) What other pathways might be possible in the complex stability landscape of the Earth System, and what risks might they entail? (*iii*) What planetary stewardship strategies are required to maintain the Earth System in a manageable Stabilized Earth state?

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