The Anthropocene as a Multi-Level Stability Landscape

Regimes, Transitions, and Reorganization of the Human–Earth System

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Abstract

Understanding the evolution of the human–Earth system over decadal-to-centennial timescales remains a central challenge in Earth system science. The Anthropocene is commonly described using trajectories, tipping elements, and scenario pathways, which capture non-linear dynamics but do not provide a unified representation of regime structure and transitions at planetary scale.

Here we introduce a conceptual framework in which the human–Earth system is represented as evolving within a multi-level stability landscape. In this representation, attractor basins correspond to alternative global configurations of human–biosphere interaction, and the Anthropocene is interpreted as a domain containing multiple regimes rather than a single trajectory. The landscape is hierarchically organized, with nested basins associated with distinct characteristic timescales.

The existence of such a landscape at planetary scale is introduced as a working hypothesis and evaluated in terms of its explanatory coherence. Within this framework, regimes are classified as viable, degraded, or crisis states, and transitions between them are path-dependent, asymmetric, and partially irreversible. The framework also represents transitions beyond the Anthropocene domain as shifts to alternative basins characterized by different modes of human–biosphere coupling.

By integrating hierarchical structure, transition asymmetry, and endogenous landscape evolution, the framework extends existing resilience and regime-shift approaches. It is conceptual and non-predictive, providing a structured representation of possible system configurations and their relationships rather than forecasting specific trajectories.

Keywords: Anthropocene; human–Earth system; stability landscape; regime shifts; resilience; complex systems; Earth system dynamics.

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1. Introduction

Understanding the evolution of the human–Earth system over multi-decadal to centennial timescales is a central problem in Earth system science. The Anthropocene is commonly defined as the period during which human activities have become a dominant driver of planetary-scale processes (Steffen et al., 2011).

Existing approaches describe the Anthropocene in terms of trajectories, tipping elements, and scenario pathways (Lenton et al., 2008; Steffen et al., 2015). These frameworks capture non-linear dynamics and abrupt transitions but do not provide a unified representation of multiple regimes, their structural relationships, and the pathways connecting them.

Here we introduce a complementary perspective in which the human–Earth system is represented as evolving within a multi-level stability landscape. In this representation, distinct regions correspond to alternative configurations of interaction between human societies and the biosphere.

A key distinction is introduced between **basins** (attractors in state space) and **domains** (regions containing multiple basins). The Anthropocene is therefore interpreted not as a single trajectory, but as a domain containing multiple regimes.
To provide a minimal formal structure, the system is represented by a reduced state vector:

$X(t) = (E, B, T, C)$,

where E denotes human environmental pressure, B biospheric integrity, T technological capacity, and C coordination capacity.

The present framework extends resilience and regime-shift approaches by (i) introducing a multi-level hierarchy of basins at planetary scale, (ii) treating the Anthropocene as a domain containing multiple regimes, and (iii) incorporating endogenous landscape evolution driven by changes in E, B, T, and C.

The objective is not predictive modeling, but a structured representation of regime structure, transitions, and landscape evolution. The framework therefore shifts the description of the Anthropocene from trajectories in time to regions and transitions in a structured state space.

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2. Stability Landscape Framework

The human–Earth system is represented as evolving within a stability landscape defined over a reduced state space. This landscape is an effective representation of system dynamics, capturing relative stability and transition structure without assuming a unique scalar potential.

The system is described by:

$X(t) = (E, B, T, C)$

with dynamics:

$$dX/dt = F(X, t)$$

The choice of variables (E, B, T, C) reflects a minimal representation of the dominant couplings in the human–Earth system at planetary scale. Environmental pressure E captures the aggregate intensity of human forcing on the Earth system, while biospheric integrity B represents the capacity of ecological and biogeochemical processes to absorb, regulate, and respond to that forcing. Technological capacity T mediates the efficiency and form of human interactions with the environment, influencing how pressure translates into impact, while coordination capacity C reflects the degree to which collective action, governance, and institutional structures can regulate system behavior.

This reduced representation does not resolve regional heterogeneity or sectoral complexity but is intended to capture the leading-order interactions governing large-scale regime structure and transitions. Attractor basins correspond to regions toward which trajectories converge (Holling, 1973; Scheffer et al., 2001).

The landscape is hierarchically organized (Figure 1):

- meta-basins (centennial–millennial)
- adaptive basins (decadal–centennial)
- scenario basins (annual–decadal)

The landscape co-evolves with the system: changes in B, T, and C modify F, reshaping basin structure.

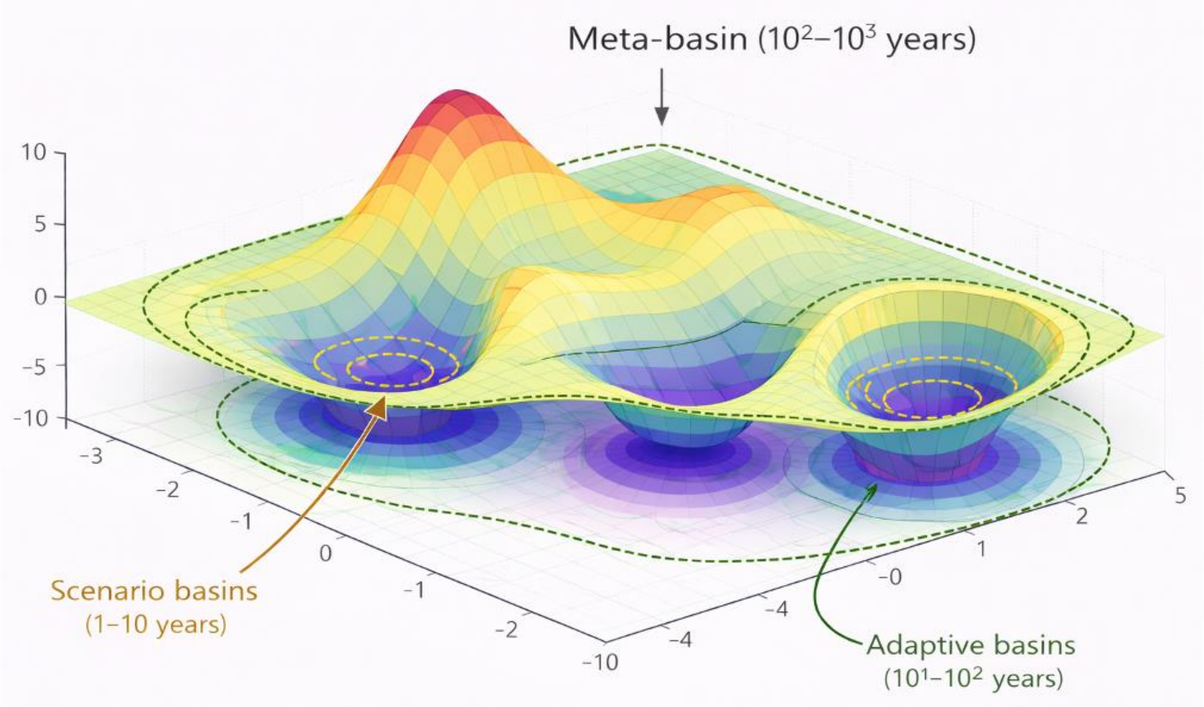

Figure 1. Hierarchical stability landscape of the human–Earth system. Schematic representation of the human–Earth system as a multi-level stability landscape defined over a reduced state space. The vertical dimension represents an abstract measure of stability, while horizontal dimensions represent system

configurations. Nested attractor basins are organized across characteristic timescales: scenario basins (years to decades), adaptive basins (decades to centuries), and meta-basins (centennial to millennial scales). Basin depth represents relative stability, and ridges represent transition barriers. The landscape is conceptual and co-evolves with the system, reflecting changes in human–biosphere interactions driven by technological, institutional, and ecological processes.

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3. Empirical Grounding and Epistemic Status

The multi-level stability landscape is introduced as a working hypothesis. It is not directly observable but provides a structured representation of regime diversity and transition dynamics.
Observed heterogeneity reflects variability within configurations rather than simultaneous realization of multiple global basins.

The framework is evaluated by explanatory power and consistency with known dynamics (Lenton et al., 2008; Steffen et al., 2015).

It suggests testable signatures, including clustering in reduced state space and hysteresis.

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4. Regimes within the Anthropocene Domain

The Anthropocene is defined as a domain in state space where human systems exert dominant planetary influence.

We introduce an effective stability functional:

$S = S(E, B, T, C)$

S should be interpreted as an effective ordering of stability rather than a directly measurable quantity.

To interpret regimes physically, define two thresholds:

- S_v: persistence threshold
- S_c: instability threshold

These are qualitative boundaries, not measurable constants.

Viable regimes
$S > S_v$: Stable configurations with sufficient B, T, C relative to E.
Degraded regimes
$S_c < S \leq S_v$: Reduced resilience, proximity to transition boundaries.
Crisis regimes
$S \leq S_c$: High variability and transition likelihood.

To represent the structure of transitions within the Anthropocene domain, we introduce a schematic state-transition diagram (Figure 2). In this representation, nodes correspond to classes of regimes in the reduced state space X(t) = (E, B, T, C), and directed links represent possible transitions between them. The diagram provides a topological view of regime connectivity, complementary to the geometric representation of basin structure shown in Figure 1.

Beyond their definition through stability thresholds, these regime classes also differ in their dynamical properties. Viable regimes are characterized by strong negative feedbacks that damp perturbations and maintain system organization, whereas degraded regimes exhibit weakened feedbacks and increased sensitivity to external and internal fluctuations. Crisis regimes, in contrast, are dominated by destabilizing feedbacks or insufficient buffering capacity, leading to amplified variability and a higher likelihood of transition. In this sense, the distinction between regimes reflects not only position in state space, but also differences in the balance of stabilizing and destabilizing processes governing system dynamics.

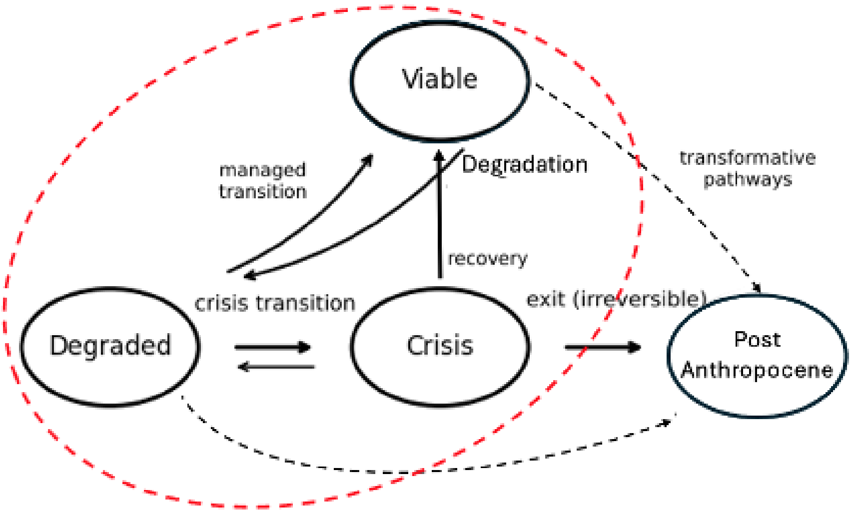

Figure 2. State-transition structure of regimes within the Anthropocene domain. Schematic transition network consistent with the basin structure shown in Figure 1. Nodes represent classes of regimes—viable, degraded, and crisis—within the Anthropocene domain (dashed boundary), as well as post-Anthropocene configurations outside it. Directed links represent possible transitions across basin boundaries, including degradation, recovery, managed transitions, and exits from the Anthropocene. The diagram provides a topological representation of transition pathways and does not imply quantitative rates or probabilities.

4.1 Position of current system

The current state may be interpreted as approaching viable–degraded boundaries, depending on indicators.

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5. Transition Dynamics

Transitions include degradation, crisis, recovery, and managed transitions.
They are:

- path-dependent
- asymmetric
- partially irreversible

Irreversibility arises from structural changes (Scheffer et al., 2001). These transition pathways correspond to the links represented in Figure 2.

5.1 Illustrative trajectory in reduced state space

A representative trajectory begins in a viable regime with moderate E and high B, T, and C. Increasing E and declining B shift the system toward degraded regions.
Further imbalance leads to crisis, where instability increases.
Recovery occurs if T and C increase sufficiently, restoring B.
Alternatively, continued degradation may lead to exit from the Anthropocene domain.
Managed transitions correspond to trajectories that avoid crisis through early increases in T and C.

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6. Exit from the Anthropocene

Exit corresponds to loss of dominant human coupling.
This may occur through:

- collapse-driven transitions
- transformative transitions

Post-Anthropocene regimes represent new attractor basins.

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7. Learning, Anticipation, and Transformative Capacity

System evolution is shaped by learning, anticipation, and innovation.
These modify system dynamics and reshape the landscape (Ostrom, 2009).

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8. Discussion and Implications

The framework integrates regime structure, transitions, and landscape evolution.
It extends resilience theory (Holling, 1973; Folke et al., 2010) and regime-shift theory (Scheffer et al., 2001). Figures 1 and 2 are complementary representations.

8.1 Empirical anchoring

Although conceptual, the framework can be related to observable indicators. The variable E can be approximated by global energy use, material throughput, or greenhouse gas emissions; B by indicators of biospheric integrity such as biodiversity loss, carbon cycle imbalance, or land-use change; T by measures of technological efficiency or innovation capacity; and C by proxies for governance effectiveness and institutional coordination.

Large-scale datasets, including satellite observations of radiation balance and land-use change, global carbon budget estimates, and socio-economic indicators, provide partial projections of system trajectories in this reduced space. While these proxies do not define the state vector uniquely, they suggest that clustering, hysteresis, and asymmetric transitions—central features of the framework—may be empirically detectable.

At the same time, the framework has important limitations. The reduced state representation does not capture regional heterogeneity, sectoral interactions, or the full complexity of Earth system processes, and the effective stability functional S is not directly measurable. The framework therefore does not provide quantitative predictions or precise thresholds, and different choices of variables or aggregation may lead to alternative representations of the landscape. Its role is instead to provide a coherent organizational structure within which diverse processes and observations can be interpreted, rather than a complete or uniquely determined description of system dynamics.

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9. Conclusion

The Anthropocene is interpreted as a domain within a multi-level stability landscape. System states are represented in $X = (E, B, T, C)$, with regimes defined by stability S and thresholds Sv, Sc.

System evolution corresponds to trajectories across a structured landscape, with Figures 1 and 2 providing geometric and topological views.
The landscape co-evolves with the system.

The Anthropocene is a contingent domain with multiple possible regimes and transitions.

The framework is conceptual and non-predictive, providing a unified representation of system organization. Future work should identify empirical signatures of basin structure and transitions.

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