Title	Before the Threshold: Deceptive Stability, Buffer Slack, and Earth System Transitions
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Before the Threshold

Deceptive Stability, Buffer Slack, and Earth System Transitions

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Abstract

Earth history includes episodes in which persistent biological or geophysical byproduct loads are absorbed by finite environmental sinks and buffers, preserving apparent stability while the capacity to absorb further stress declines. This paper synthesizes literatures on Earth system revolutions, redox transitions, mass extinctions, and Anthropocene change into a comparative framework termed Buffered Byproduct Regime Shift (BBRS). BBRS organizes such transitions into a six-phase sequence from load emergence and buffered accumulation during a Deceptive Stability Interval to threshold crossing, selective mortality, and successor-regime reorganization. The paper's contribution is diagnostic and comparative. It brings persistent load, sink-mediated lag, declining buffer capacity, observable pass-through, selective vulnerability, and successor-regime structure into a single evidentiary sequence for evaluating when apparent stability is being maintained by continued buffer function despite declining regime compatibility. The framework distinguishes gradual saturation from threshold-collapse buffer failure, introduces graded case membership, and uses the K-Pg event as a negative-control discriminator. It is applied to the Great Oxidation Event, the end-Permian crisis, the Ediacaran–Cambrian transition, the PETM, and the Anthropocene. Across these cases, BBRS also distinguishes byproduct valence: whether accumulated waste becomes an exploitable free-energy gradient for successor regimes or remains spent material that tightens constraints until a closure pathway is built. In this framing, false negatives, trait-selective vulnerability, institutional lag, and degraded archives become linked expressions of the same architecture: functioning buffers can suppress ambient change while transferring risk into slack loss, spatial heterogeneity, preservation loss, or dependence on a filtered baseline. Slack loss may therefore appear first as spatial patchiness, incomplete recovery between cycles, source/sink divergence, proxy dropout, or archive degradation before familiar observables respond. The Anthropocene application frames intervention timing as a problem of whether a system producing its own destabilizing load can recognize declining buffer slack before the calm produced by buffering reinforces the forcing that closes the effective intervention window.

Keywords: Earth system transitions; Great Oxidation Event; end-Permian extinction; Anthropocene; buffer slack; critical transitions; sink-mediated lag; Deceptive Stability Interval; byproduct accumulation; intervention window; hyperthermals

1. Introduction

1.1 Context in Prior Literature

Comparative Earth system science has long treated major transitions as coupled reorganizations of energy capture, material cycling, feedback structure, and ecological architecture.[1] Lenton, Pichler, and Weisz (2016) describe deep-time innovations and human industrialization as revolutions in energy input and material cycling, emphasizing that long-run stability depends on the re-closure of disrupted cycles. That framing coheres with redox-based interpretations of Earth history that treat major oxygenation episodes as balances among sources, sinks, feedbacks, and reservoir coupling.

The Great Oxidation Event (GOE) is the canonical redox example. The rise of atmospheric oxygen is routinely interpreted as a source–sink problem in which oxygenic production, reductant sinks, and burial/oxidation feedbacks jointly govern redox state (Lyons, Reinhard, and Planavsky, 2014; Holland, 2006; Canfield, 2005). In this literature, the long delay between inferred oxygenic photosynthesis and sustained atmospheric oxygenation is not paradoxical; it is a sink-mediated lag. In such cases, buffering can maintain an apparently ordinary world across spans so long that the underlying disequilibrium is not merely hard to detect but difficult for organisms, institutions, and even retrospective intuition to scale correctly.

Mass-extinction literatures provide a second set of related cases in which persistent forcing and feedbacks reorganize background constraints. The end-Permian crisis (ca. 252 Ma) is widely interpreted as a coupled volcanogenic forcing and climate–ocean–biosphere collapse involving warming, stratification, acidification, oxygen loss, and cascading ecosystem failure. Erwin (2006) and Wignall (2015) emphasize multi-causal kill webs rather than monocausal toxicity narratives while still recognizing that altered ocean redox structure and circulation are central to both extinction intensity and recovery duration.

The Ediacaran–Cambrian transition is a more contested locus where environmental constraints, ecological escalation, and evolutionary innovation intersect. Knoll (2003) stresses causal pluralism; substrate revolution, redox heterogeneity, predation, and ecosystem engineering all matter. That very ambiguity makes the interval a useful stress test for any comparative framework: a serious framework must be able to include such cases without overstating confidence.

Finally, the modern Anthropocene is assessed in official syntheses, most importantly IPCC AR6 Working Group I (2021), which emphasizes observationally constrained warming, ocean heat uptake, carbon-cycle partitioning, ocean acidification, and risks of nonlinear responses in certain subsystems. The tipping elements framing (Lenton et al., 2008) and the broader critical transition literature (Scheffer et al., 2001; Scheffer et al., 2009; Dakos et al., 2012) supply language for threshold behavior, hysteresis, resilience loss, and early-warning structure under sustained forcing.

1.2 The Gap BBRS Targets

The gap addressed here is more specific than a missing account of thresholds, resilience loss, sinks, or feedbacks. Those concepts already do substantial work in the existing literature. What is less developed is a way to compare cases in which apparent stability is itself an empirical signal requiring explanation. In many Earth system settings, the pre-threshold condition is produced by reservoirs, reaction pathways, circulation structures, living systems, or institutional arrangements that absorb load while losing capacity. BBRS is proposed for that narrower class of transitions. It identifies cases in which stability should be read with suspicion because an identifiable buffering architecture may still be translating accumulating load into hidden slack loss before visible state change appears.

This changes the analytical emphasis. A threshold analysis can ask whether a state variable is approaching a critical point. A BBRS reading asks which buffer is suppressing the state-variable response, whether that suppression is weakening, whether more of the same forcing is reaching observable domains, and whether later reorganization favors forms less dependent on the buffered baseline. The comparison is organized around an ordered relation: persistent load, buffer-mediated

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[1] Vernadsky (1926) argued that the biosphere functions as a geological force in its own right, that living matter, through its metabolic outputs, engineers planetary redox and material cycling at civilizational and deep-time scales.

delay, slack depletion, observable pass-through, selective vulnerability, and successor-regime structure.

1.3 What is Established Prior Art Versus Synthesis-level Novelty

The framework proposed here is built from well-established ingredients. Earth system transitions have long been described in terms of reorganized energy capture, material cycling, sink structure, and feedbacks; the GOE is already understood as a source–sink redox problem; the end-Permian as a coupled crisis with interacting kill mechanisms; and Anthropocene change as a case of partitioned sinks, inertia, and possible nonlinear subsystem responses. None of that is claimed as new here; the argument is about how those pieces fit together across cases. BBRS elevates buffer slack as a variable for cross-case comparison, gives explicit phase form to the interval in which buffering preserves apparent stability while its remaining capacity declines, and uses graded membership plus a negative-control comparison to distinguish stronger from weaker cases. The field-level contribution is to make apparent pre-threshold stability diagnostic in its own right. In BBRS, persistence can reflect the expenditure of finite buffering capacity, and false negatives before threshold crossing can be produced by buffering itself.

The central move is an interpretive inversion. BBRS does not ask only whether a system is approaching a threshold; it asks when buffering makes the system appear farther from the threshold than it is. Strain may accumulate first as declining slack rather than as visible change in the state of the system. Apparent stability isn't neutral background information. It is a possible system output: a filtered residual produced by sinks, buffers, and reservoirs that may be losing the very capacity that makes the system look stable. Under persistent net load, the evidentiary value of stability changes with cumulative loading: the longer a finite buffer preserves a stable residual without independent evidence of slack restoration, the less that residual can be read as safety. Buffers temporarily substitute for cycle closure, absorbing loads faster than biological, geochemical, or technological pathways can re-assimilate them. In the Anthropocene, this problem becomes reflexive: the system producing the load can interpret buffer-produced calm either as warning evidence or as permission to keep scaling the forcing that consumes the buffer. BBRS does not claim priority over thresholds, sinks, or lags; it claims that their ordering changes the evidentiary meaning of stability, acceleration, missingness, selectivity, and recovery across Earth system transitions.

1.4 Relation to Tipping Element and Critical Transition Frameworks

BBRS overlaps with tipping element and critical transition literatures in its concern with nonlinear change, hysteresis, and threshold behavior (Scheffer et al., 2009; Dakos et al., 2012). Critical transition work has long shown that large state changes may be preceded by little visible movement in the state variable itself (Lenton et al., 2008; Scheffer et al., 2009). BBRS accepts that general insight but asks a narrower question: what if the apparent calm is being produced by the continued expenditure of specific sinks and buffers that temporarily absorb the load, rather than by generic resilience loss alone? The distinction is that buffering architecture becomes the primary object of comparison. Buffering does more than delay transition: it shapes warning structure, the duration of deceptive persistence, and whether threshold approach appears as smooth deterioration, spatial patchiness, or abrupt structural failure. It also helps determine which organisms, ecological strategies, or institutions become vulnerable because they remain calibrated to the buffered baseline. The emphasis is on sink-mediated lag, buffer slack depletion, the Deceptive Stability Interval, and graded case membership across heterogeneous Earth system transitions. Rather than replacing tipping element or critical-transition frameworks, BBRS refines their scope by identifying a narrower class of transitions in which buffering architecture becomes the central object of comparison.

Given this narrower focus, the comparable object is the relation among source, buffer, observable residual, threshold behavior, and successor regime. That relation allows lagged stability to be interpreted case by case: in some systems persistence may reflect continued compatibility between forcing and buffering, while in others it may mark the expenditure of hidden slack. Framing the comparison this way allows heterogeneous cases to be compared without reducing them to a single mechanism or treating resemblance as equivalence.

1.5 What BBRS Changes Analytically

BBRS sits inside the wider literature on tipping elements and critical transitions, but it narrows the problem to cases where buffering architecture governs what can be observed before reorganization. The distinction has practical consequences. When apparent stability is treated as background, monitoring usually privileges state variables and generic early-warning indicators. When apparent stability is treated as a produced residual, the analyst must also ask how much load is being withheld from observation by sinks, reservoirs, circulation structures, living systems, or other buffers, and whether that withholding capacity is degrading.

The difference can be summarized as a shift in diagnostic priority:

Analytical question	**Common emphasis in adjacent frameworks**	**BBRS diagnostic emphasis**
Why has the state variable not moved more?	State variables can remain stable while resilience, recovery rate, or threshold margin changes.	Apparent stability is interpreted through an identifiable source-buffer-residual relation: which load is being absorbed, which buffer is absorbing it, and what independent evidence shows that remaining capacity is declining?
What does acceleration in an observable mean?	Forcing, feedback strength, or state-variable sensitivity may be increasing.	Residual acceleration is decomposed into source acceleration versus declining pass-through suppression; the same forcing can become more visible as buffer efficiency weakens.
What should be monitored before threshold crossing?	State variables, variance, autocorrelation, recovery rate, and threshold proximity.	Each state variable should be paired with its forcing term and an independent buffer-performance measure, such as sink efficiency, carbonate or redox capacity, heat uptake structure, incomplete recovery, or source/sink divergence.
How should missing or degraded archives be interpreted?	Missingness is commonly treated as uncertainty, preservation bias, or loss of temporal resolution.	Archive degradation becomes BBRS-relevant only when it covaries with independently inferred buffer stress; process-coupled missingness is a testable signal, not an assumed explanation.
What constrains successor-regime pathways?	Survivorship, ecological release, altered boundary conditions, dispersal, and recovery dynamics.	Byproduct valence constrains whether the altered medium offers an exploitable gradient, a tolerable stressor, or a closure debt requiring external work, biological uptake, or geochemical compensation.
What kind of framework is being proposed?	Adjacent frameworks may be formal, empirical, or conceptual depending on application.	BBRS is a diagnostic ordering framework; it does not claim calibrated prediction unless load, buffer capacity, and residual response can be independently estimated.
What prevents elastic case expansion?	Cases are often grouped by threshold behavior, nonlinear response, or resilience loss.	BBRS requires an ordered sequence: persistent load, independent buffer mediation, declining slack, altered pass-through, and selective reorganization. Cases lacking that sequence remain comparisons, candidates, mixed press-pulse cases, or exclusions rather than positive cases.
What excludes a case?	Exclusion criteria may be implicit or case-specific.	Severe consequence is insufficient. A BBRS interpretation weakens when the main transition is organized by acute shock, when pre-threshold buffer mediation is absent, or when declining slack cannot be independently supported.

Table 1. Diagnostic distinction between BBRS and adjacent tipping, resilience, and critical-transition frameworks.

This is the reason for treating BBRS as a bounded framework rather than a metaphor. Its value does not come from grouping together more examples of abrupt change. Its value comes from specifying the evidence that strengthens, weakens, or excludes a case. A strong BBRS interpretation requires more than severe consequence. It requires an ordered sequence in which persistent loading is mediated by buffers, slack declines, visible signals become less filtered, and reorganization selectively penalizes dependence on the buffered baseline.

2. Framework and methods

2.1 Conceptual Definition of BBRS

A Buffered Byproduct Regime Shift (BBRS) is a transition class characterized by a persistent byproduct load that accumulates under sink/buffer mediation and reorganizes the system nonlinearly once buffering slack is sufficiently depleted.

A functional definition uses four minimum conditions: persistent net load; independent sink/buffer mediation; slack depletion; and thresholded reorganization with ecological selectivity. The framework is thus broader than a single kill mechanism but narrower than a generic claim that "systems can tip."

- Persistent net load: a byproduct load accumulates due to sustained forcing such that $(F - R) > 0$ over the relevant interval.
- Sink/buffer mediation: sinks and buffers absorb enough net load to delay or mask baseline shift, producing a lag interval.
- Slack depletion: buffering effectiveness declines measurably or structurally as buffer slack, $\Sigma(t)$, approaches zero.
- Thresholded reorganization: baseline chemistry, circulation, or habitat partition shifts nonlinearly, with possible hysteresis.

2.2 Six-phase Grammar

BBRS is expressed as a six-phase grammar:

1. Phase A — Flux emergence or amplification: persistent increase in an environmentally consequential load input.
2. Phase B — Buffered accumulation / Deceptive Stability Interval: sinks and buffers absorb net load, creating apparent stability while consuming slack.
3. Phase C — Sink strain and slack depletion: buffering effectiveness declines and susceptibility rises.
4. Phase D — Threshold crossing and rapid background shift: baseline chemistry, circulation, or habitability partition reorganizes.
5. Phase E — Selective mortality and functional rewrite: specialists of the prior regime are disproportionately harmed; ecosystem constraints are rewritten.
6. Phase F — Reorganization and radiation under the new baseline: survivors or pre-adapted marginal strategies expand under new background constraints.

In practice, slack depletion may first appear as spatial fragmentation of buffering rather than as globally uniform decline, so localized failures can form the bridge between Phase C sink strain and Phase D threshold crossing.

Calling Phase B the Deceptive Stability Interval keeps a central risk in view: apparent stability can be produced by the very buffering structures whose remaining slack is shrinking.

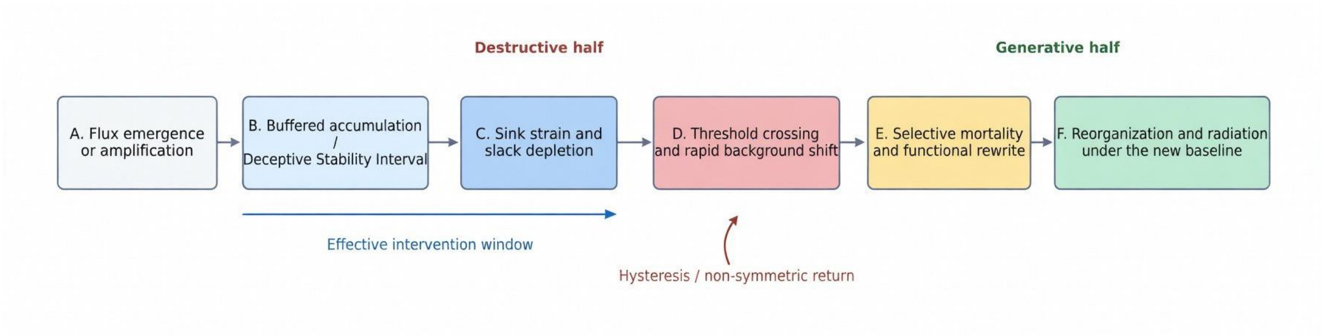

Figure 1. BBRS phase grammar, showing the Deceptive Stability Interval, the split between destructive and generative halves, and the effective intervention window before threshold crossing.

2.2.1 Why Deceptive Stability Is Structurally Produced

The Deceptive Stability Interval is usually described as an interpretive hazard: buffered calm gets mistaken for safety. But the problem is not only interpretive. It's also a consequence of how buffering works.

A buffer does not merely delay the environmental consequence of loading. It can translate accumulating load preferentially into reservoir depletion rather than into strong ambient change in the medium that organisms, ecosystems, or institutions directly experience. Where this translation is effective, the instability is real but located within the buffer reservoir (unobserved residual capacity, or dark slack), a geochemical domain outside the signal environment against which selection, adaptation, and institutional response are calibrated. Apparent stability is exactly what a functioning buffer should produce, which is also what makes it unreliable as a safety signal.

The relationship between Phase B and Phase E is sharper than the standard framing makes explicit. Selection operating during Phase B may continue to favor success under a baseline whose persistence depends on ongoing buffer expenditure. Specialists of the prior regime were shaped by successful adaptation to a filtered baseline whose stability depended on buffering structures already under depletion. Phase E selective mortality becomes the delayed cost of adaptation calibrated against conditions that buffer expenditure was making progressively less representative of the underlying trajectory, rather than just an external pruning event. The timescales involved deserve emphasis. The Deceptive Stability Interval of the Great Oxidation Event lasted on the order of 200 million years: a span so large it resists intuitive grasp. Consider that if Earth's entire 4.5-billion-year history were compressed into a single calendar year, the interval between the first oxygen-producing bacteria and atmospheric oxygenation would occupy roughly sixteen days. Normal human cognition has no scaffold for this. Yet the mechanism operating across that interval was not exotic: bacteria photosynthesized, reductants reacted, sinks depleted, grain by grain, reaction by reaction, with nothing dramatic visible at any moment. The math of deep time is the framework's silent engine. A process operating at one meter of net change per ten thousand years accumulates twenty-five kilometers of consequence per 250 million years. It is precisely this quality, that nothing alarming is happening at any given moment while everything is changing across the relevant interval, that makes the Deceptive Stability Interval something more than a descriptive label. It is a structural feature of how slow processes and finite buffers interact across time, and it operates whether or not any observer is present to misread the calm.

This connection runs through to Phase F. Forms that were marginal under prior-regime conditions, including those inhabiting buffer-edge zones or engaging more directly with the byproduct medium, were subject to less complete signal filtering during Phase B. So their pre-adaptation to post-transition conditions is consistent with having been selected against a baseline less insulated from the byproduct load the transition eventually makes ambient. The generative and destructive halves of BBRS aren't structurally independent; they share a common origin in the signal-filtering properties of buffering architecture during Phase B.

2.3 Destructive and Generative Halves

BBRS integrates two halves that are often discussed separately. The destructive half (B→E) tracks buffered disequilibrium, slack depletion, threshold crossing, and selective mortality. The generative half (E→F) tracks the release of ecological opportunity and the expansion of strategies that were previously marginal or suppressed under the prior regime.

Successor regimes often do not wait for wholly new exploiters to appear after transition. As Section 2.2.1 suggests, pre-adapted forms may already exist at low abundance, and transition may simply remove the competitive conditions that kept them marginal. The framework therefore links collapse to successor dominance rather than treating them as separate problems.

Phase F shouldn't be read as ordinary recovery after damage; it marks the moment when traits, metabolisms, life habits, or institutional forms that were previously marginal become newly compatible with the altered background medium. The transition doesn't necessarily invent the successor regime from nothing; it can expose the prior regime's hidden selectivity by revealing which forms were already less dependent on the buffered baseline that has just failed.

2.4 Regime Succession by Residue versus Niche Colonization of Residue

BBRS does not treat every instance of waste use as equivalent. It distinguishes local niche colonization of residue from cases in which residue helps reorganize the background medium itself.

Feature	Local residue niche use	BBRS regime succession
Scale of byproduct effect	Local or patch-scale accumulation creates a niche without reorganizing the background state.	Persistent byproduct load accumulates at regional, ocean-basin, atmospheric, or Earth system scale.
Role of sinks and buffers	Residue is exploited or tolerated locally; background buffering is not the main control on system timing.	Sinks and buffers delay expression of the load, creating a Deceptive Stability Interval and declining slack.
Observable stability	Stability outside the niche remains largely irrelevant to the residue user.	Apparent stability becomes a system output produced by active buffering.
Threshold behavior	No necessary regime-scale threshold follows from the niche itself.	Slack depletion can produce thresholded reorganization once buffering no longer contains the load.
Successor-regime consequence	The residue user occupies an available niche within the existing regime.	The byproduct helps restructure the regime, selecting against prior-regime specialists and favoring tolerant, pre-adapted, or newly advantaged forms.
Byproduct valence	Usually secondary; the key issue is local exploitability.	Potentially decisive: the accumulated byproduct may become a usable gradient or substrate, or remain spent waste requiring external work or slow geochemical closure.

Table 2. This distinction separates ordinary exploitation of a residue from regime succession driven by persistent byproduct accumulation. BBRS requires more than a niche opportunity: it requires sink-mediated lag, declining buffer slack, thresholded reorganization, and successor-regime consequences tied to the altered background state. Byproduct valence is introduced here only as a boundary condition; its Phase F implications are developed later in the paper.

The point is to reserve BBRS for cases in which accumulated byproducts stop being local niche phenomena and begin to help reshape broad ecological or geochemical constraints of the regime.

2.5 Buffer Failure Modes

BBRS distinguishes two buffer failure modes that affect warning structure and intervention prospects. Type I buffers decline through comparatively continuous exhaustion of absorptive or neutralizing capacity. The governing structure is closer to cumulative consumption or asymptotic weakening of an existing buffer. In Earth system terms, this resembles progressive sink degradation or finite chemical buffering being consumed over time.

Type II buffers depend on the persistence of a structural or metastable regime, so that failure occurs not mainly through smooth exhaustion but through reorganization of the buffering subsystem itself. This resembles circulation, stratification, habitat architecture, or other state-dependent structures that continue to buffer load until a threshold is crossed, after which buffering deteriorates rapidly. The distinction is between capacity exhaustion and buffer-structure reorganization.

2.5.1 Reactive and Indirect Byproduct-Buffer Interactions as a Cross-Cutting Modifier

Buffer failure mode is one axis of comparison. Another concerns how the byproduct interacts with the buffer itself. In some cases, the chemistry of buffering also consumes the buffer; in others, degradation is more indirect and proceeds through structural or state-dependent pathways. This second distinction cuts across Type I and Type II rather than replacing them, but it helps explain why Phase C does not take the same form across cases.

Direct interaction between byproduct and buffer changes the pace of deterioration. Oxygen consumes the reductant sinks buffering it. CO_2 works against carbonate buffering through the same chemistry that absorbs it. Under sustained forcing, those cases can steepen as buffering weakens, even without any increase in source strength. By contrast, more indirect pathways, e.g. thermal loading affecting circulation, tend to look flatter until structural change takes over.

This cross-cutting modifier may help explain why superficially similar loading histories produce different Phase C geometries across cases. In the Anthropocene, carbonate buffering involves direct reactive interaction while ocean heat uptake and cryosphere-albedo feedbacks involve more structurally indirect degradation pathways. Recognizing which subsystem belongs to which category bears on how Phase C trajectories and monitoring signals should be expected to differ across them and adds mechanistic texture to the coupled-buffer picture developed in Section 5.3.

Buffers need not be purely passive reservoirs; in some cases, Earth system or biospheric processes can partially reinforce or regenerate buffering, so that BBRS depends not only on finite capacity but on whether byproduct loading outpaces buffer reinforcement. In such cases, the Deceptive Stability Interval may reflect not only passive buffer drawdown but active buffering upregulation, which can temporarily slow slack decline and alter the shape of $\Sigma(t)$ and the structure of early-warning signals. More generally, BBRS depends not only on cumulative net load but on the relation between forcing timescale and buffer replenishment or recovery timescale. A given cumulative load may remain bufferable when forcing is slow relative to replenishment, but can drive thresholded reorganization when forcing is rapid relative to the system’s capacity to restore or redistribute buffering. Many Earth system drivers and recovery processes are cyclic rather than monotonic, so BBRS should be read as a net-ratchet framework rather than a one-way staircase. Cycles remain outside BBRS when low-load phases restore the slack lost during high-load phases. They become BBRS-relevant when successive cycles leave a residual deficit, widen the oscillatory envelope, or make threshold crossing dependent on the coincidence of a forcing maximum with weakened buffering. Phase B and Phase C can include repeated near-misses: apparent returns toward baseline that do not fully reset slack. A final transition may then appear to be caused by the last forcing pulse, even though the critical condition was cumulative loss of threshold margin across prior cycles.

This rate sensitivity links BBRS to rate-induced tipping: the same cumulative forcing can remain bufferable under slow movement through state space but trigger reorganization when forcing outruns recovery, redistribution, or closure pathways. BBRS adds the buffer-specific claim that dangerous rate is defined not only by the external driver, but by the system's remaining capacity to absorb, re-route, or re-close the byproduct cycle (Ashwin et al., 2012; Ritchie et al., 2023).

Active reinforcement also helps explain why Phase B lasts so much longer in some cases than in others. Where biological or ecological processes reinforce buffering, through organic burial, mat persistence, ecosystem processing, or living-system uptake, the interval of apparent stability can last much longer than passive reservoir depletion alone would suggest (Canfield, 2005; Lyons, Reinhard, and Planavsky, 2014; Seilacher, 1999; Buatois et al., 2014; IPCC, 2021; Friedlingstein et al., 2025). Where those same processes weaken or reverse, Phase B can shorten quickly, sometimes faster than aggregate flux accounting implies. In the τ_F / τ_R terms introduced here, active reinforcement effectively shortens the recovery timescale of buffering relative to passive replenishment alone; when that reinforcement weakens or fails, the timescale lengthens, and Phase C can steepen even without a proportional rise in source flux (IPCC, 2021; Friedlingstein et al., 2025).

Some buffers are biosphere-mediated in a more literal sense. Forests, wetlands, soils, planktonic systems, and other living assemblages can store, transform, or redirect environmentally consequential loads for long periods while accumulating stress of their own. Forest dieback, for example, can mean more than ecological damage; it can remove carbon storage and moisture-recycling capacity at the same time. Coral-reef collapse and mass bleaching likewise mark the loss of living structures that had stabilized local chemical and ecological conditions. Changes of that kind are not just downstream effects of stress. They can also accelerate Phase C by weakening removal capacity and turning stabilizing systems into amplifiers of subsequent change (IPCC, 2021; Friedlingstein et al., 2025).

In cases where buffering is actively upregulated during Phase B, early-warning structure may be delayed, damped, or temporarily stabilizing rather than monotonically destabilizing. Apparent persistence can then reflect compensatory reinforcement as well as passive reserve drawdown. On this reading, BBRS occurs when byproduct loading ultimately outpaces the rate at which buffering can be generated, reinforced, or redistributed, such that stabilizing signals give way to renewed slack decline.

This typology connects BBRS to tipping element and critical transition thinking without collapsing the two. Standard early-warning expectations may be reshaped by buffering structure itself: some systems may show familiar resilience-loss signals, whereas others may defer, damp, or spatially fragment those signals while slack is still being spent. The framework's distinctiveness lies in treating buffers as the comparative object whose failure mode shapes the temporal geometry of regime shift and intervention-window closure. The practical implication is that BBRS depends not only on how much load accumulates, but on whether the pace of forcing outstrips the pace at which buffering can recover, regenerate, or redistribute (Scheffer et al., 2009; Dakos et al., 2012).

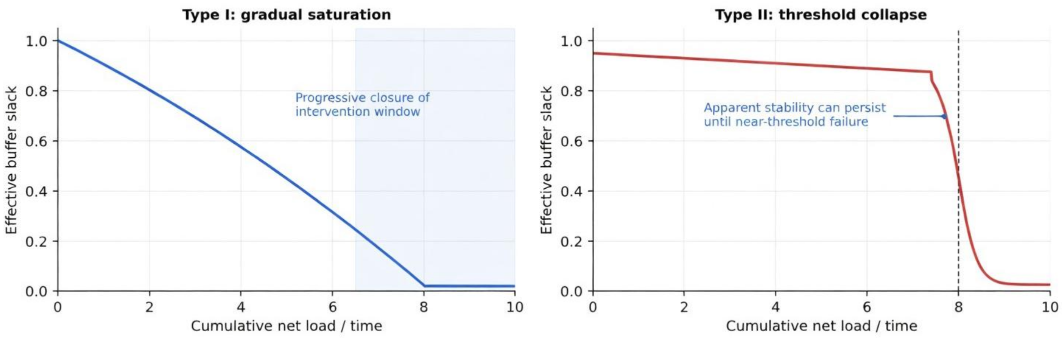

Figure 2. Conceptual buffer-failure modes. Type I buffers show progressive saturation and gradual intervention window closure; Type II buffers can preserve apparent stability until near-threshold slack loss produces a sharp rise in reorganization risk. Curves are stylized and not fitted to empirical data.

2.6 Methods and Graded Membership

The paper traces a recurring topology across established literatures and then asks how far it travels across cases with different evidentiary status. The issue isn't whether the cases are ultimately the same kind of event; it's whether a common grammar clarifies comparison better than loose analogy does.

The case labels are methodological rather than taxonomic. The GOE is treated as canonical because the lag structure and thresholded reorganization are comparatively direct. The end-Permian is treated as compound because several interacting stressors appear to realize the topology together. The Ediacaran–Cambrian interval is used as a candidate case to generate discriminative expectations without claiming settled membership. The Anthropocene is treated as an application in which partitioning is observed directly but trajectories remain contingent. Proxy ambiguity, uneven temporal resolution, and reflexivity, especially in the Anthropocene, remain substantial constraints. BBRS is offered as an interpretive scaffold and test program, not as a universal explanation for abrupt change.

3. Empirical Signatures and Discrimination

The point of this section is simple: BBRS should exclude some abrupt transitions. The signatures below show what a positive case should look like, and the K-Pg comparison helps show what should count against classification.

3.1 Empirical Signature Checklist

Operationally, BBRS classification depends on evidentiary ordering. A strong case should show sustained load being mediated by an identifiable sink or buffer, followed by weakening buffer performance, incomplete recovery, spatial fragmentation, or archive degradation before or during reorganization. The transition should also show selective vulnerability linked to dependence on the buffered baseline. Abrupt consequences alone are insufficient; the framework requires a meaningful history of sink-mediated lag and slack depletion.

Signature family	BBRS expectation	Typical evidence types	Primary inferential risk
Persistent net accumulation	Sustained $(F - R) > 0$ over the relevant interval.	Reservoir trends, flux proxies, partitioning budgets.	Flux often inferred indirectly in deep time.
Sink / buffer mediation	Independent sinks or buffers absorb load during the lag interval.	Sink deposits, redox buffers, ocean heat/ carbon uptake, carbonate-state trends.	Multiple sinks can mimic each other.
Slack depletion	Buffer proxies indicate declining buffering effectiveness or structural weakening.	Sink efficiency shifts, circulation/ventilation indicators, chemical capacity measures.	Proxy resolution may be insufficient.
Threshold indicators	Comparatively step-like shift in baseline chemistry, circulation, or habitability.	Abrupt proxy transitions, facies change, diagnostic isotope or redox signal shifts.	Apparent abruptness can be a stratigraphic artifact.
Selective mortality	Specialists of the prior regime are disproportionately harmed.	Trait-linked selectivity, habitat partition change, extinction structure.	Sampling, geography, and trait uncertainty confound inference.
Release / radiation	Expansion of forms suited to the reorganized baseline.	Post-crisis radiations, opportunist dominance, ecological restructuring.	Radiation can be delayed by persistent stress.
Hysteresis potential	Recovery path differs from departure path.	Persistent altered states, slow recovery, state dependence.	Delayed recovery can have multiple causes.

Table 3. Empirical signature checklist for BBRS membership.

The checklist is meant to discipline case classification. A BBRS reading strengthens only when the evidence appears in the expected order: sustained load, buffer-mediated delay, weakening buffer performance or incomplete recovery, followed by thresholded reorganization with selective consequences. Abruptness alone is insufficient. Severity alone is insufficient. The order matters.

This is especially important in deep-time applications. The strongest evidence is rarely a single proxy excursion. It is covariance among load indicators, buffer-state indicators, preservation conditions, and ecological selectivity. Archive degradation should not automatically be treated as missing information outside the process. Dissolution, proxy dropout, facies loss, or reduced temporal resolution may carry information if they occur where and when buffer stress is independently expected. The stronger claim is limited: process-coupled missingness should covary with inferred slack loss; random preservation loss should not.

This gives the framework a direct observational test. If proxy dropout, archive thinning, or preservation degradation shows no relation to independent indicators of buffer stress, the strong BBRS interpretation weakens. If those losses covary with buffer stress, the damaged archive becomes part of the transition signal.

3.2 Negative-control Discrimination

Abrupt change alone is not enough for BBRS. The framework is meant for cases in which sustained load accumulates, buffering delays full reorganization, and slack is consumed before threshold crossing. Shock-dominated events can produce severe transition without that sequence, which is why a negative control is necessary here.

This exclusionary function is what makes the framework portable without becoming indiscriminate. A useful synthesis gains power by specifying which tempting examples should be rejected, rather than gathering more examples under a larger label. K-Pg is included for that reason: it resembles BBRS cases in consequence, but not necessarily in causal topology.

Feature	**BBRS-consistent expectation**	**Shock-dominated negative control (K-Pg exemplar)**
Dominant pre-transition driver	Sustained flux or load accumulation.	Acute exogenous shock dominates.
Deceptive Stability Interval	Present and meaningful.	Absent or negligible.
Independent sink-mediated lag	Required.	Not required.
Slack depletion before transition	Central diagnostic.	Not central.
Threshold marker	Often present as a reorganization point.	Present, but tied to shock arrival.
Main lethality structure	Baseline shift plus stress cascade.	Shock effects dominate.
Recovery shaping	Strongly structured by the altered baseline medium.	Recovery structured chiefly by post-shock conditions.

Table 4. Negative-control discriminator using the K-Pg event.

The K-Pg comparison is included to sharpen the boundary of the framework. If an event lacks a meaningful pre-transition interval in which sustained net load is being absorbed by sinks and buffers while their remaining slack declines, it should tend to fall outside BBRS.

The K-Pg case is not invoked as a chemically simple or single-cause event. Deccan volcanism makes the boundary more complex than a pure impact-only control. Its use here is narrower: K-Pg tests whether abrupt consequence alone is sufficient for BBRS membership. A BBRS reading would require evidence that sustained pre-boundary loading was absorbed through a Deceptive Stability Interval in which declining slack, rather than acute shock forcing, organized the main transition. If that evidentiary ordering cannot be shown, K-Pg should remain outside the framework or be treated as a mixed press-pulse boundary case rather than a positive BBRS exemplar.

The negative-control function is essential because BBRS concerns a particular causal ordering, not the scale of consequence. Shock-dominated events can restructure ecosystems, climate, and sedimentary archives without passing through a meaningful Deceptive Stability Interval. Such events may share recovery problems with BBRS cases, but their pre-threshold structure differs. This is why K-Pg is useful despite its geological complexity. The issue is not whether K-Pg was simple. The issue is whether its main transition was organized by cumulative closure debt accumulated through sink-mediated lag. Without that ordering, K-Pg belongs at the boundary of the framework rather than within its positive case set.

The exclusion strengthens the comparison. A framework that accepts every abrupt transition becomes vocabulary. A framework that rejects tempting cases because the evidence appears in the wrong order becomes a classification tool.

Under the byproduct-valence and closure-debt framing, K-Pg also clarifies BBRS boundary conditions: enormous ecological consequence does not make a transition BBRS if the main event was not preceded by closure debt accumulated through sink-mediated lag. Mixed press-pulse cases should be assessed by whether the press component, rather than the acute pulse, organized the diagnostic sequence.

A shock-dominated boundary may leave a relatively discrete event marker even when its ecological consequences are severe, while a BBRS case should show a preceding interval where sustained forcing was mediated by sinks or buffers, with slack loss expressed through suppressed, displaced, or degraded signals before reorganization. BBRS is most applicable where regime change is plausibly tied to cumulative forcing plus buffering architecture, not solely to instantaneous shocks.

4. Case Studies

The framework is applied here to four principal cases: the GOE, the end-Permian crisis, the Ediacaran–Cambrian transition, and the Anthropocene. They do not carry the same evidentiary status. The GOE is the strongest canonical case, the end-Permian is treated as compound, the Ediacaran–Cambrian interval is used as a hypothesis program, and the Anthropocene is treated as an ongoing application. Table 5 also includes the PETM as a rate-sensitive comparator. More detailed operationalization and phase-mapping tables are left to the appendices.

Case	Membership	Dominant load / flux	Dominant sinks / buffers	Lag character	Threshold indicators	Dominant kill mechanisms	Phase F character
Great Oxidation Event	Canonical	Biological O_2 production plus burial feedbacks	Reductant sinks and redox buffering networks	Long sink-mediated lag	Major atmospheric /redox proxy transitions, including loss of large sulfur MIF signals (Farquhar et al., 2000)	O_2 toxicity to obligate anaerobes and habitat repartition	Expansion of O_2-tolerant and later O_2-using metabolisms; successor regime specifically exploits the new redox medium
End-Permian crisis	Compound	Volcanogenic Forcing plus cascading redox stress	Carbonate buffering; ventilation/ circulation capacity	Deceptive stability followed by accelerating slack loss	Sharp biodiversity collapse aligned with carbon-cycle and redox disruption	Multi-stressor kill web: heat, acidification, hypoxia/anoxia, ecosystem cascade	Recovery dominated by flexible, opportunistic, and generalist survivors rather than a single new energetic substrate
Ediacaran–Cambrian transition	Candidate	Ecological engineering plus redox/habitat feedbacks	Sediment microenvironment buffering and substrate regime	Patchy and basin-dependent	Substrate/habitat reorganization and turnover	Habitat disruption plus ecological escalation	Candidate shift toward mobility, interaction, and engineering strategies if the topology applies

Paleocene–Eocene Thermal Maximum (PETM)	Rate-sensitivity candidate	Rapid carbon injection	Carbonate buffering and ocean circulation	Comparator for forcing-pace versus buffer-recovery mismatch	Carbonate-buffer stress and climate–ocean reorganization (McInerney & Wing, 2011; Zeebe et al., 2016)	Not mapped here as a canonical BBRS kill web	Full membership unresolved; included as a rate analogue rather than a co-equal mapped pillar
Anthropocene carbon era	Application	CO_2 emissions and land-use forcing	Ocean heat uptake, carbonate chemistry, land/ocean uptake, circulation structures	Clear inertia with measurable buffering	Observed trends plus assessed tipping risks	Ongoing ecosystem disruption, extremes, ocean stressors	Indeterminate and ongoing; candidate successor traits include resilience under altered thermal, chemical, and disturbance regimes

Table 5. Comparative case table. The added Phase F column restores explicit treatment of the generative half of BBRS.

“Phase F character” is included to prevent BBRS from being read purely as a collapse framework. It specifies the structure of successor dominance and the extent to which pre-adaptation is identifiable before or during transition.

4.1 Great Oxidation Event (canonical)

The Great Oxidation Event (~2.45–2.32 Ga) serves as the canonical case because the lag between inferred oxygenic photosynthesis and sustained atmospheric oxygenation is comparatively direct evidence of sink-mediated delay rather than a contested inference from ambiguous proxies. Oxygenic photosynthesis is inferred to have emerged earlier, but atmospheric oxygenation was delayed by sinks and reservoir coupling. The core empirical fact is that oxygen could be produced for a long interval without immediately reorganizing the atmosphere because reductant sinks and redox buffers dominated the budget.

That long pre-GOE interval is interpretable as a Deceptive Stability Interval: oxygenic production was already altering the system, yet the atmospheric baseline remained superficially stable because buffering structure still had slack. Convergence among proxy families, most notably the disappearance of strong sulfur mass-independent fractionation signals, marks the thresholded background shift that justifies canonical status. The sulfur MIF signal is one of the clearest threshold markers for major atmospheric redox reorganization, following the foundational interpretation of Farquhar, Bao, and Thiemens (2000).

The generative half matters here. The successor regime is not random survival; it is specifically the expansion of oxygen-tolerant and eventually oxygen-using metabolisms (Raymond and Segrè, 2006). The new baseline is not merely tolerated. It becomes energetically constitutive of the successor regime.

4.2 End-Permian Crisis (compound)

The end-Permian extinction (~252 Ma) is the framework’s most important compound case because several interacting stressors jointly consume slack and reorganize the system rather than simply one byproduct becoming the new background medium. Siberian Traps forcing increased greenhouse load and contributed to warming, stratification, acidification, oxygen loss, and ecosystem collapse. These stresses interacted through a coupled kill web rather than a monocausal pathway.

BBRS remains useful here because the core logic is preserved: sustained forcing, partial masking by carbonate chemistry and circulation structure, loss of buffering slack, and threshold-like ecological and geochemical reorganization. The case is especially important for the framework because it shows that BBRS need not mean “one waste product takes over”; it can also apply to multiply realized byproduct crises in which several coupled loads jointly consume slack.

The characterization of end-Permian buffering as Type II should be treated as heuristic and qualitative rather than definitive. Basin-scale heterogeneity in proxy patterns remains substantial, so the claim is that structural circulation and redox buffers plausibly behaved in threshold-collapse fashion in at least part of the system; not that every basin or interval did so in the same way.

Phase F here is not the arrival of one new dominant energetic substrate analogous to oxygen. Instead, the successor regime is characterized by ecological release of flexible, opportunistic, and generalist survivors under altered baseline constraints.

4.3 Ediacaran–Cambrian Transition as BBRS Hypothesis Program

The Ediacaran–Cambrian interval matters here precisely because its causal structure remains disputed. Rather than treating it as a co-equal pillar, the paper uses it as a hypothesis program. This preserves its value as a stress test without pretending that BBRS membership is already established.

What matters here is whether the transition exhibits the signatures expected if a buffered habitat or micro-redox regime were progressively destabilized before larger-scale ecological reorganization.

This hypothesis-program framing sits alongside classic work on biomat-related lifestyles and the substrate revolution (Seilacher, 1999; Bottjer, Hagadorn, and Dornbos, 2000), as well as later demonstrations that matground ecology persisted into the earliest Cambrian (Buatois et al., 2014).

BBRS component	**Predicted BBRS pattern**	**Empirical target**
Deceptive Stability Interval	Evidence of progressive destabilization of matground-sustaining redox microgradients before full dominance of bioturbation or substrate reorganization.	Geochemical indicators of weakening microenvironmental redox structuring prior to major ichnological/substrate transition.
Slack depletion	Progressive disruption of stabilizing habitat or buffer structures before major turnover.	Timing and expansion of bioturbation/ substrate-revolution markers.
Threshold indicators	Relatively sharp habitat-partition reorganization aligned with biotic turnover.	Synchronization of matground-to-mixground transition with turnover pulses.
Selective mortality	Disproportionate loss of taxa dependent on prior substrate or microenvironment structure.	Trait-linked turnover patterns and habitat associations.
Release / radiation	Expansion of mobile, ecologically interactive, or engineering strategies after habitat reorganization.	Changes in community structure and ecological interaction indicators.
Buffer failure mode	Type II behavior is more likely if habitat structure is metastable rather than gradually saturating.	Evidence of abrupt substrate-regime change rather than only smooth drift.

Table 6. Ediacaran–Cambrian as a BBRS hypothesis program rather than a settled mapping.

The progressive-destabilization prediction is the most discriminative BBRS-specific test in this table. Matground persistence by itself does not distinguish BBRS from other substrate-revolution accounts. The stronger claim is that one should find evidence of weakening microenvironmental redox structuring before full substrate revolution becomes dominant. Absent that ordering, the Ediacaran-Cambrian interval should remain a useful comparison case rather than a BBRS member.

4.4 Anthropocene Application

The Anthropocene differs from pre-human cases because the producing system is reflexive. Emissions, carbon-cycle partitioning, ocean heat uptake, and some candidate nonlinear subsystem risks are directly observed rather than inferred solely from deep-time proxies. BBRS functions here as a leverage and timing framework rather than a deterministic forecast. More specifically, the producing system can observe changes in E, infer changes in Σ, and alter F, R, and in some cases B through coordinated intervention. Reflexivity thus introduces a feedback from system observation back into load generation and buffering preservation, even though BBRS does not model that feedback quantitatively here.

Reflexivity can also amplify the load rather than only correct it. When buffering keeps damages below economic, political, or institutional alarm thresholds, the filtered residual can subsidize continued forcing by making the costs of load generation appear lower, more distant, or more manageable than they are. In that case, Phase B doesn't just delay response; it can help reinforce F(t) until visible deterioration arrives after socio-economic dependence on the load has deepened.

The Anthropocene is a reflexive closure test. The producing system can observe its own waste accumulation, but carbon dioxide and heat do not become a high-power successor medium in the way oxygen later became an electron-acceptor opportunity; the task is to use external non-fossil energy and institutional coordination to re-close carbon, nitrogen, land-use, and material cycles before biospheric and geochemical buffers stop substituting for closure.

Observation of slack loss can itself become a causal factor in whether the transition is slowed, redirected, or merely endured. This is especially important where living systems function as buffers in their own right, since degradation of forests, wetlands, soils, reefs, or marine productivity can turn partial stabilizers into amplifiers of subsequent change. Modern coral reefs may provide a particularly legible Anthropocene example of this living-buffer problem. Reef systems can retain apparent ecological identity while their carbonate-production function is already being rewritten: declining coralgal calcification, increasing bioerosion, altered benthic composition, and reduced net carbonate production may precede or outpace the visible disappearance of reef structure. In BBRS terms, the relevant signal is not only coral cover or bleaching frequency, but whether the reef's sedimentary and geochemical function is shifting from a tropical coralgal carbonate factory toward lower-accretion, heterozoan, microbial, or non-framework carbonate assemblages under combined acidification, warming, eutrophication, and ecological stress. If detectable in dated reef cores, such a shift would make the Anthropocene application unusually concrete: a living buffer would not merely be damaged; it would begin recording its own transition into the geological archive as a change in carbonate-production mode.

The Anthropocene is a measured case of persistent byproduct loading distributed across coupled buffers. Ocean heat uptake, terrestrial and marine carbon uptake, carbonate chemistry, sea ice, cryosphere state, and circulation structure do not behave as one uniform reserve. They differ in capacity, time constant, and failure mode, and they do not weaken in synchrony. Earlier references to slack are therefore shorthand for a coupled architecture, not a claim that the contemporary Earth system is governed by one homogeneous store of buffering capacity. These structures are linked by transport, circulation, albedo, moisture recycling, carbon-cycle partitioning, and other teleconnections, so strain in one domain can shift burden to another. A subsystem that first appears regional or sectoral may narrow intervention capacity elsewhere by redistributing stress through the larger buffering architecture, allowing slack loss to propagate through the system rather than remain locally bounded (Liu et al., 2023).

The Anthropocene application is more specific than the claim that human forcing may push Earth system components toward thresholds. That conclusion is already established. The BBRS-specific claim is that modern societies may mistake continued buffer function for continued regime compatibility. Ocean heat uptake, land and ocean carbon absorption, carbonate chemistry, cryosphere inertia, soil storage, wetland function, reef accretion, insurance systems, emergency management, and infrastructure redundancy can all reduce the immediate visibility of forcing while narrowing future response capacity. The world can remain operational because compatibility is being purchased through buffer expenditure.

This matters for the interpretation of acceleration. If atmospheric, oceanic, ecological, or disaster-related indicators worsen faster than forcing alone would imply, the change may record declining pass-through suppression. The central monitoring question becomes: how much of each additional unit of forcing is now escaping the buffering architecture? That question connects climate monitoring to carbon-cycle partitioning, carbonate chemistry, ecosystem condition, insurance losses, emergency-management capacity, and infrastructure reliability. It also turns the Anthropocene into a timing problem: visible deterioration may arrive after the effective intervention window has already narrowed.

Unlike the deep-time cases, Anthropocene Phase A is not a single isolated flux, but a synchronized acceleration generated by a reflexive socio-economic system: energy use, land transformation, fertilizer production, greenhouse-gas emissions, and material throughput rose together during the Great Acceleration (Steffen et al., 2015). This synchrony imposed a coupled demand pulse on distributed Earth system buffers whose capacities, thresholds, and recovery times remain asynchronous; apparent continuity in headline observables can therefore coexist with uneven hidden slack loss across the underlying Earth system architecture.

Figure 3 schematizes how synchronized human forcing can impose a coupled load on Earth system buffers whose capacities, thresholds, and recovery times remain distributed and asynchronous.

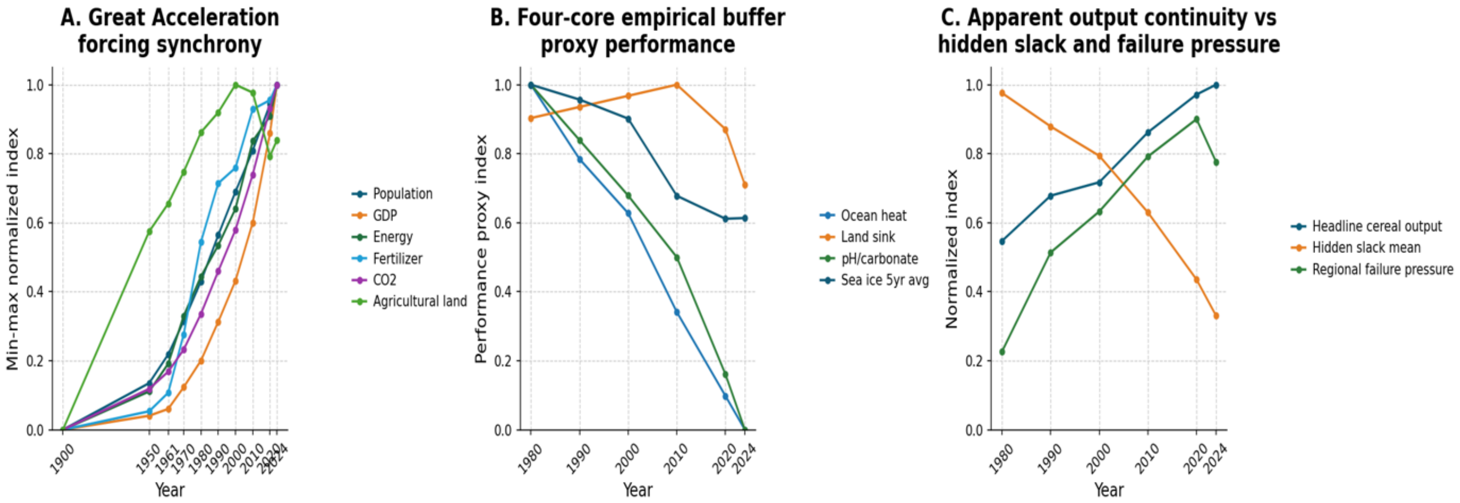

Figure 3. Great Acceleration synchrony as Anthropocene Phase A forcing topology and empirical BBRS proxy dynamics. Panel A shows selected long-run forcing indicators (population, real GDP, primary energy use, nitrogen fertilizer use, atmospheric CO2, and agricultural land) normalized from the cited Great Acceleration and long-run data sources (Steffen et al., 2015; Our World in Data, n.d.; Maddison Project Database, n.d.; Energy Institute, 2025; Food and Agriculture Organization of the United Nations, 2025; NOAA Global Monitoring Laboratory, n.d.). Panel B shows author-normalized empirical buffer-performance proxies for ocean heat content, land carbon sink fraction, surface ocean pH, and Arctic September sea-ice extent using a trailing 5-year average for sea ice (NOAA National Centers for Environmental Information, n.d.; Friedlingstein et al., 2025; Our World in Data, n.d.; National Snow and Ice Data Center, n.d.). Panel C compares global cereal-production continuity, the four-proxy hidden-slack index, and disaster-event/damage pressure (Food and Agriculture Organization of the United Nations, 2025; CRED/UCLouvain, 2026; Our World in Data, n.d.). All indices are author calculations from real data and are intended as comparable visualization proxies, not direct physical capacity limits.

What BBRS adds here is not the observation that contemporary societies monitor buffers, sinks, or threshold risks; that is already well established. The sharper point is interpretive and structural. Monitoring is often organized around subsystem-specific indicators or visible state change, whereas a coupled buffering architecture can continue to produce an apparently governable world precisely by absorbing load into declining slack. Continued sink uptake, heat absorption, or regional persistence may therefore be read as partial safety even when they are functioning instead as mechanisms of reservoir depletion, stress redistribution, and narrowing intervention capacity elsewhere in the system. In this sense, the central diagnostic question is not only whether change is being observed, but whether observed persistence is being correctly interpreted: not as reassurance by default, but as a possible output of buffering structures whose residual stabilizing capacity is being spent. Functioning buffers can still project calm. That projection should not be treated as reassurance by default; it may be the signature of remaining stabilizing capacity being spent.

4.5 Effective Intervention Window

For the Anthropocene, the practical issue is timing. The effective intervention window is the period during which reductions in F, protection or enhancement of R, and reinforcement of B can still avert threshold crossing or materially lessen reorganization. It depends on observed disruption, remaining slack, subsystem reversibility, and the lag between institutional action and biophysical response. In coupled systems that window need not close everywhere at once. It can narrow subsystem by subsystem, so that regional deterioration shortens lead time elsewhere. Slack loss may first appear as spatial fragmentation rather than global decline, and local sink or buffer failure may therefore signal a narrowing window before aggregate indicators fully register reorganization. The coupled-buffer mechanism that can sustain this uneven approach to closure is taken up more explicitly in Section 5.3.1.

In the Anthropocene application, this response lag can be represented as τ_I, the institutional or technological deployment timescale required to reduce forcing, enhance removal, or reinforce buffering. The intervention window narrows when τ_I approaches the remaining slack-lifetime of the relevant buffer, so that the time needed to act becomes comparable to, or longer than, the time left before threshold proximity is committed.

In practical terms, closure of the effective intervention window is not inferred from one universal metric, but from the convergence of load, lag, and deployability timescales. For Type I buffers, closure is most plausibly tracked through persistent deterioration in buffer-efficiency metrics, such as declining sink uptake efficiency, worsening carbonate saturation state, or rising airborne fraction relative to emissions. For Type II buffers, closure is less likely to appear as smooth exhaustion and more likely to appear as structural instability, for example through circulation-weakening indicators, slowing recovery after perturbation, or assessed approach to subsystem thresholds. The window is effectively closed when committed forcing plus subsystem response lag exceeds the remaining lead time over which available interventions can still prevent threshold crossing or materially reduce post-threshold reorganization.

The Type I / Type II distinction matters directly here. In Type I systems, the effective intervention window tends to close progressively as slack declines; monitoring can therefore track closure with greater continuity. In Type II systems, structural buffering can preserve apparent stability until the system is already near a threshold, such that the decision-to-deployment lag of real institutions may exceed the remaining window for system-preserving intervention.

Buffer class	Illustrative monitoring logic	Window closing signal
Type I (gradual saturation)	Track airborne fraction, weakening land/ocean sink uptake efficiency, declining carbonate saturation state, or heat uptake efficiency	Persistent deterioration in buffer performance indicates progressive closure
Type II (threshold collapse)	Track instability markers: AMOC-weakening indicators, subpolar freshening/density changes, slowing recovery, structural circulation weakening, rising variance/autocorrelation, assessed threshold proximity	Window may close before the full transition is visible; warning comes through resilience loss, not just trend

Table 7. Schematic monitoring logic for identifying closure of the effective intervention window.

This monitoring logic does not claim precise threshold prediction. Rather, it translates the framework into directional diagnostics: in Type I systems the question is whether buffer performance is deteriorating persistently; in Type II systems the question is whether resilience-loss indicators associated with critical transitions, including slowing recovery and rising variance or autocorrelation, are beginning to appear (Scheffer et al., 2009; Wang et al., 2012).

4.5.1 Observable Signals as Buffered Residuals

Observable state variables, i.e. atmospheric CO_2, ocean pH, surface temperature, sea ice extent, do not report total load directly. They register what remains after sinks and buffers have done what they can. As buffering weakens, more of the same forcing becomes visible in the ambient record.

A stable observable can mean at least two different things: either forcing remains compatible with buffering, or buffering is still concealing incompatibility by absorbing damage into reservoirs, structures, or living systems not yet visible in the headline metric. BBRS makes that ambiguity explicit rather than allowing apparent persistence to be mistaken for low risk.

That point changes how acceleration in observed state-variable change should be read. Faster visible change need not mean that forcing has accelerated by the same amount. It can also mean that absorption efficiency is deteriorating, so that a larger share of each unit of forcing now passes through to observable domains instead of being taken up into reservoir depletion. A monitoring scheme that reads accelerating observables only as evidence of intensifying forcing collapses two different dynamics into one: source acceleration and declining buffer performance.

This can be stated as an observable pass-through expectation. As buffer slack declines, a larger fraction of each additional unit of forcing should appear in the monitored state variable. In Phase B, pass-through is suppressed because sinks and buffers absorb load; in Phase C, the same forcing can produce a larger observable response as buffering efficiency weakens. Several published records already contain partial versions of this diagnostic. The point is that BBRS reads these records as histories of changing buffer performance rather than as isolated state-variable trends.

Published record / metric	Published observation	BBRS interpretation	Candidate Phase C expectation
Anthropogenic CO2 partitioning / airborne fraction	IPCC AR6 reports that during 2010-2019, about 46% of anthropogenic CO2 emissions accumulated in the atmosphere, with about 23% taken up by the ocean and 31% by land (IPCC, 2021).	Direct modern pass-through metric: the share of emitted carbon escaping land-ocean buffering into the atmosphere.	Rising or persistently high atmospheric pass-through, especially if land/ocean sink efficiency weakens relative to emissions.
Land and ocean carbon-sink efficiency	IPCC AR6 treats land and ocean sinks, airborne fraction, and sink efficiency as linked carbon-cycle diagnostics (IPCC, 2021).	Buffer-performance metric: the capacity of biological and oceanic sinks to absorb a given anthropogenic load.	Declining uptake per unit forcing, or growing divergence between regions/subsystems that remain sinks and those shifting toward source behavior.
Ocean heat uptake / Earth energy inventory	IPCC AR6 identifies ocean heat uptake as the dominant reservoir of climate-system heat accumulation. Forster et al. report that Earth's energy imbalance has more than doubled since 1976-1995 (IPCC, 2021; Forster et al., 2026 preprint).	Heat uptake is a buffer-performance record: apparent atmospheric continuity partly reflects energy being stored in ocean reservoirs.	Changing heat-uptake efficiency, regional heat-storage divergence, or increased surface response per unit forcing as thermal buffering becomes less effective or redistributes.
Carbonate saturation / pH trajectories	IPCC AR6 assesses ocean CO2 uptake, carbonate chemistry, ocean acidification, and related biogeochemical feedbacks (IPCC, 2021).	Chemical-buffer diagnostic: carbonate saturation and pH trends record how added CO2 is being partitioned into ocean chemistry.	Increasing chemical response per unit carbon load as carbonate buffering weakens, especially in low-capacity or high-exposure regions.
Reef carbonate production / accretion	Cornwall et al. project major global declines in reef net carbonate production under ocean warming and acidification (Cornwall et al., 2021).	Living-buffer diagnostic: reef carbonate factories can lose accretion function before visible reef identity fully disappears.	Declining net accretion, increasing bioerosion, or carbonate-factory transition before simple coral-cover metrics indicate full ecological collapse.
Paired deep-time load/response proxies	PETM and other hyperthermal records pair inferred carbon release with carbonate dissolution, temperature, biotic, and ocean-chemistry responses (McInerney and Wing, 2011; Zeebe et al., 2016).	Deep-time pass-through analogue: paired source/load and response proxies can test whether more of the load became visible as buffering weakened.	Increasing environmental response per unit inferred load, with proxy uncertainty and preservation loss treated as part of the diagnostic problem.
GOE source-sink oxygen proxy structure	Lyons, Reinhard, and Planavsky describe early oxygenation as a source-sink balance in which O2-consuming reactions initially delayed persistent atmospheric O2 accumulation until	Canonical deep-time pass-through case: biological O2 production was buffered by reductant sinks until enough O2 passed through to reorganize atmospheric/oceanic redox	Intermittent or stepwise observable oxygenation as source production increasingly exceeded reductant buffering capacity.

Published record / metric	Published observation	BBRS interpretation	Candidate Phase C expectation
	sources overcame sinks (Lyons et al., 2014).	baseline.	

Table 8. Published metric families interpretable as BBRS pass-through diagnostics. The records are not new; the BBRS contribution is to read them together as partial histories of changing buffer performance and observable pass-through.

State-variable trends and buffer-performance metrics have to be read together. The key question is what the current rate of observable change implies about remaining slack under weakening absorption. Flux reduction remains essential, but observable change can also accelerate when buffering deteriorates even without a proportional increase in source strength. Monitoring that tracks only the observable cannot separate those pathways or judge intervention timing well.

A useful candidate example is the Atlantic Meridional Overturning Circulation (AMOC). BBRS does not treat AMOC as a proven imminent collapse. It treats it as a plausible Type II-style buffer candidate: a structural circulation regime whose threshold location is uncertain, whose early-warning indicators may be imperfect or ambiguous, and whose reorganization could be difficult to reverse on societally relevant timescales once committed. On this reading, the Anthropocene is not only a byproduct-loading problem but a timing problem: whether reflexive action can occur before the effective intervention window closes across the most consequential coupled subsystems.

4.6 Lever Map without Policy Overreach

The framework is not itself a policy program, but it does clarify which classes of action bear on its central variables:

- Reduce F — reduce emissions and other byproduct fluxes.
- Preserve or enhance R — sustain removal pathways and sink integrity.
- Preserve or enhance B — protect buffering structures and the resilience of key subsystems.
- Account for failure mode — interpret Type I and Type II buffers differently when assessing warning structure and intervention-window closure.

The practical implication is straightforward. Temperature and carbon-budget metrics remain necessary, but they are not enough on their own. They need to be read alongside measures of sink integrity, buffer performance, and the condition of the structures whose apparent persistence can conceal the most consequential deterioration. At societal scales, BBRS reframes national-security risk as a problem of buffered dependence: infrastructure, supply systems, insurance regimes, emergency management, and mission-critical services can remain calibrated to baseline conditions that active buffering has made temporarily reliable. The decisive vulnerability is strategic warning lag: institutions may keep treating buffered normalcy as a planning baseline after declining buffer performance has already made that baseline obsolete (National Intelligence Council, 2021; U.S. Department of Defense, 2021). For risk assessment, the key distinction is between genuine stability and stability purchased by declining buffer slack: records calibrated to headline observables, from stable carbon uptake and persistent reef structure to insurable losses and supply continuity, can understate post-threshold risk and keep decisions tied to a regime already spending down its stabilizing capacity. The failure-mode distinction sharpens this problem. Type I buffer degradation may allow iterative adjustment as deterioration registers progressively in performance metrics, but Type II failure can preserve apparent structural stability until threshold proximity is already committed. At that point, institutional decision-to-deployment lags may exceed the remaining intervention window, leaving exposures calibrated to the buffered baseline the last to register the timing risk they carry.

5. Discussion

5.1 What BBRS adds to Earth System Theory

BBRS adds to Earth system theory by shifting attention from the moment of threshold crossing to the buffering architecture that shapes observability before threshold crossing. Thresholds, resilience loss, sink limitation, redox balance, carbonate compensation, ecological selectivity, and recovery dynamics are established topics (Lenton et al., 2008; Scheffer et al., 2009; Dakos et al., 2012; Lyons, Reinhard, and Planavsky, 2014). The contribution here lies in their ordering. BBRS treats apparent pre-threshold stability as a residual that must be explained: a signal produced when an identifiable buffer absorbs load quickly enough to delay visible reorganization, even as its remaining capacity declines.

Buffer slack is used here more narrowly than resilience. It refers to the remaining capacity of specified sinks, reservoirs, or buffering structures to absorb, neutralize, or redistribute a persistent load before that load appears in the observable state variable. The diagnostic question is concrete: which capacity is producing the apparent stability, and how would its weakening alter the observable record?

The narrower question is whether a persistent byproduct load is being translated into buffer depletion before it appears as ambient change. That framing separates two dynamics that can look similar in monitoring records. Observed acceleration may arise from stronger forcing. It may also arise from declining absorption efficiency, as a larger fraction of the same forcing escapes into the monitored state variable. These diagnoses imply different evidence. Source acceleration points to the forcing record. Declining pass-through suppression points to sink efficiency, source/sink divergence, carbonate or redox capacity, heat-uptake structure, incomplete recovery between cycles, and spatially uneven buffer failure (IPCC, 2021; Friedlingstein et al., 2025).

The same ordering clarifies selectivity. Phase E mortality is more than a post-threshold pruning event. In BBRS, it can represent the delayed cost of adaptation to a baseline that buffering had made increasingly unrepresentative of the underlying trajectory. Taxa, ecological strategies, or institutions most dependent on the filtered baseline should be most exposed when buffering fails. Forms already occupying buffer-edge environments, tolerating the byproduct medium, or living closer to the emerging baseline may be better positioned for Phase F expansion.

BBRS also distinguishes successor regimes by byproduct valence. Some accumulated byproducts become exploitable gradients or substrates under the new regime. Others remain dissipated residues that require external work, biological uptake, geochemical compensation, or technological closure. Oxygen is the canonical harvestable byproduct: initially toxic to obligate anaerobes, later recruited as a high-power electron acceptor. Carbon dioxide and heat differ because they are largely spent products of high-power metabolism and combustion. Their accumulation does not by itself supply an equivalent energetic successor regime. This distinction prevents the Great Oxidation Event, hyperthermals, mass extinctions, and the Anthropocene from collapsing into a superficial analogy. They may share buffer-mediated lag while differing sharply in closure pathway (Falkowski and Godfrey, 2008; Lyons, Reinhard, and Planavsky, 2014; Lenton et al., 2016). The added value lies in the ordering of evidence. The six-phase grammar disciplines that ordering by making buffer-produced stability, declining slack or incomplete recovery, selective dependence on the buffered baseline, and successor-regime release parts of one diagnostic sequence. It turns resemblance into a set of expectations about lag structure, slack depletion, observable pass-through, threshold crossing, selectivity, and successor dominance. The distinction between gradual saturation and threshold-collapse buffer failures then bears directly on warning structure and intervention timing, while negative controls prevent the framework from expanding into a catch-all account of abrupt change.

The Deceptive Stability Interval has a social and perceptual analogue in what Pauly (1995) termed shifting baseline syndrome: the tendency of each generation to calibrate normalcy against the conditions it first encounters, such that gradual deterioration becomes invisible across generational timescales. BBRS suggests that this perceptual dynamic has a physical substrate: buffering structures actively produce the stable signal against which organisms, ecosystems, and institutions are calibrated.

The shifting baseline is not merely a failure of memory or attention. It is in part a consequence of how buffering works.

5.2 Limits

Conceptual frameworks risk becoming too elastic. BBRS responds by requiring a specific signature combination: persistent net load, sink-mediated lag, slack depletion, and thresholded reorganization. The negative-control comparison with K-Pg is meant to show explicitly what the framework should exclude.

The end-Permian remains heterogeneous in proxy expression. BBRS treats it as compound and carries forward an explicit caveat: the Type II characterization of circulation or redox buffering is suggestive, not definitive, because basin-scale heterogeneity remains substantial.

The Ediacaran–Cambrian interval remains plural and contested. The framework's contribution there is to generate a more discriminative test program, not to claim settled membership.

The Anthropocene should not be read deterministically. BBRS explicitly rejects inevitability. A reflexive producer can alter F, influence R, and try to preserve B; the question is whether this can happen before the effective intervention window closes in key subsystems.

Whether BBRS improves on looser analogy remains an empirical question. Its value does not rest on claiming that sources, sinks, selectivity, or thresholds are new objects of study; they are not. The value lies in how it arranges those objects and what it asks the analyst to notice first. In the Anthropocene application, acceleration in atmospheric CO_2, temperature, pH, or related observables is not treated only as a stronger forcing signal. It may also indicate that absorption efficiency is declining as slack is spent. Source acceleration and buffer failure call for different diagnostics, and state variables alone cannot separate them. The Phase B / Phase E relation makes a similar move. Selective mortality is not simply a post-threshold pruning of vulnerable taxa; it may also mark the delayed failure of traits fitted to a baseline that buffering had made progressively less representative of the system's underlying trajectory. The question for selectivity data then changes: not only which organisms died, but which forms were most dependent on conditions maintained by a shrinking buffer. These are real inferential differences. The framework earns its keep only where it changes the search pattern: toward pre-threshold buffer performance, source/sink divergence, process-coupled missingness, incomplete recovery between cycles, or selectivity tied to dependence on a filtered baseline. If they hold across cases, BBRS is more than a new label; if they do not, its scope should remain limited to the cases where the buffer-centered reading changes the diagnosis.

5.3 Scalar Slack as Simplification

Treating slack as a single comparative variable is useful, but only up to a point. In the Anthropocene, and probably in some deep-time cases as well, buffering is distributed across partially coupled subsystems with different capacities, recovery times, threshold timings, and modes of failure. Ocean heat uptake, carbonate buffering, land carbon uptake, cryosphere state, and circulation integrity do not weaken together or in the same way. A scalar slack term keeps the framework usable, but it also smooths over a more uneven reality in which strain can be redistributed among coupled buffers and the apparent persistence of the whole can hide sharp deterioration in one part. A fuller account of BBRS, especially in Anthropocene applications, would treat slack as coupled rather than singular. This is especially true where living systems form part of the buffering itself, since regional ecological breakdown can erode not only local resilience but the wider system's capacity to absorb, store, or redistribute load.

Treating slack as scalar is a comparative convenience. Earth system buffering isn't singular, smooth, or evenly distributed, and the framework doesn't require it to be. The coupled account specifies where the framework's core logic requires supplementation: wherever buffering is asynchronous, spatially uneven, or networked in ways the scalar version erases.

5.3.1 Compensatory Redistribution Near Threshold

In coupled systems, stress can move. One pathway weakens, another absorbs more of the burden, and global averages can remain steadier than the underlying structure deserves. That is one reason apparent stability can persist so close to threshold.

Heterogeneity is informative here. When some subsystem indicators worsen while others hold, the pattern is not just noise around a stable mean. It may show that redistribution is still working, but under rising strain. In that setting, divergence across regions or subsystems can mark a late Phase C condition that global averages blur.

This implies a diagnostic inversion: in late Phase C, the mean state may be less informative than the spatial distribution of failure. Rising patchiness, source/sink sign reversals, clustered local breakdowns, or persistent regional divergence should not automatically be treated as noise around a stable aggregate. In a coupled buffering architecture, patchiness may be the first visible geometry of slack loss: local buffers fail before the global mean admits that the larger system is reorganizing.

In BBRS, spatial heterogeneity can be the visible geometry of Phase C. Where buffering capacity is uneven, slack loss should first appear at buffer edges, in low-capacity regions, or in subsystems bearing redistributed load. A stable global mean can then coexist with a structured geography of declining buffer performance.

This prediction can be tested with existing spatial datasets. BBRS does not treat regional divergence in acidification, sink behavior, reef carbonate production, or disturbance response as noise around a global mean. It treats such divergence as a possible Phase C geometry: slack loss should appear first where buffering capacity is thin, recovery is incomplete, or exposure to less-filtered load is already high, then propagate or redistribute through coupled systems.

Spatial record / setting	Published observation	BBRS interpretation	Phase C spatial expectation
Regional ocean acidification gradients	The western Arctic has acidified three to four times faster than other ocean basins, linked to sea-ice loss and changing surface-ocean exposure (Qi et al., 2022).	Acidification is not spatially uniform; buffer loss appears first where physical buffering and carbonate chemistry are already exposed or weakened.	Fastest pass-through should occur in low-buffer or newly exposed regions, with acidification fronts expanding from buffer-thin margins.
Mapped surface-ocean acidification indicators	Mapped monthly OA products now resolve pH, aragonite saturation, and related indicators at fine spatial scales for U.S. large marine ecosystems from 1998-2022 (Sharp et al., 2024).	Spatially explicit OA data can be read as buffer-performance maps rather than only as regional environmental-condition maps.	Phase C should show structured clusters of declining carbonate-buffer performance, not random local variability.
Ocean carbon-sink divergence across basins	Recent work decomposes decadal trends in the ocean carbon sink across major ocean basins and links most trend variation to atmospheric CO2 growth, with additional effects from internal variability and ocean heat uptake (Terhaar, 2024).	Basin-scale sink differences are candidate records of uneven carbon-buffer performance and redistribution.	Divergence among basin sinks should increase where heat uptake, circulation, or carbon chemistry weaken uptake efficiency.
Land carbon-sink regional variability	Global vegetation-model work reports a large net land sink while emphasizing regional/source-sink differences and drivers such as CO2 fertilization, climate, and land-use effects (Sitch et al., 2024).	Land sinks are distributed buffers, not one homogeneous reservoir.	Phase C should appear as regional source/sink divergence before the global land sink clearly fails.
Thermally variable reefs	Corals from thermally variable American Samoa reef habitats show heat-resistant populations; genomic work found heat-associated alleles more common in warm microclimates (Palumbi et al., 2014; Barshis et al., 2013).	Thermally variable reefs are buffer-edge environments where biological response is already being selected under less-filtered thermal load.	Reef trajectories should diverge according to thermal-buffer history, with stress-tolerant assemblages emerging first at thermal edges.
Naturally low-pH reef gradients	Palau studies found coral communities persisting across natural pH gradients, with community changes across lower-pH conditions (Shamberger et al., 2014;	Naturally acidic reefs are carbonate-buffer-edge settings where acidification exposure is already partly ambient.	Lower-pH reef zones should preview acidification-tolerant assemblages, altered calcification, or lower-accretion carbonate states.

Spatial record / setting	Published observation	BBRS interpretation	Phase C spatial expectation
	Barkley et al., 2015).		
Global reef carbonate production	Cornwall et al. project global declines in reef net carbonate production under warming and acidification, with trajectories sensitive to coral cover and community tolerance (Cornwall et al., 2021).	Carbonate-production decline is a living-buffer performance metric, not only a reef-health metric.	Phase C should appear as spatially uneven net-accretion decline before simple reef-identity metrics fully collapse.

Table 9. Published spatial records interpretable as Phase C geometry under BBRS. The table does not claim that spatial heterogeneity proves BBRS membership. It identifies existing datasets that can test whether buffer weakening appears first as structured regional divergence, buffer-edge deterioration, or uneven pass-through before global means fully register reorganization.

Cyclic forcing allows he same pattern to appear through time. Slack loss may register as incomplete recovery between cycles before it appears as a directional shift in the mean: widening amplitude, lower recovery floors, rising skew, repeated near-misses, or increasing sensitivity to forcing maxima that previously remained bufferable. A stable mean can mask an unstable envelope.

For the Anthropocene, this shifts monitoring and the overall focus from global aggregates alone to divergence among coupled subsystem buffers. A system in which some buffering pathways are deteriorating while others appear stable may represent a more deeply advanced Phase C than aggregate metrics would suggest, especially if the pathways showing apparent stability are absorbing redistributed load rather than operating under baseline conditions.

In some coupled buffering systems, spatial fragmentation may be more than a descriptive precursor to threshold crossing. Where compensation depends on connectivity among partially coupled buffering units, local failures can accumulate while broader system function is preserved through rerouting and redistribution. Threshold approach can resemble loss of a system-spanning compensatory network: once connectivity falls below a critical level (analogous to connectivity thresholds in spatially coupled systems), local deterioration no longer remains local and broader reorganization can proceed rapidly.

This coupled-buffer extension is especially important for understanding cascade risk in the Anthropocene, where subsystem interactions may produce stronger nonlinearities than any single-buffer model would imply. Global reorganization need not begin as a globally uniform process. In some cases, deterioration may begin as clustered regional failures whose cumulative interaction alters the load-bearing role of larger Earth system buffers. Localized or regional buffer failures can increase effective load on adjacent subsystems through teleconnections, redistribution, or circulation change, making spatial heterogeneity a plausible bridge between Phase C and Phase D. This is especially relevant where regionally differentiated failures may precede system-wide reorganization, and where the analyst's error is to treat persistent global averages as evidence that the larger buffering architecture remains securely intact (Liu et al., 2023; IPCC, 2021).

5.4 Why Successor Regimes Need Not Await De Novo Innovation

Successor regimes may arise less from post-transition innovation than from the release of forms that were already present but ecologically constrained under the prior regime. In the GOE, the successor regime is not random survival but the expansion of oxygen-tolerant and eventually oxygen-using metabolisms under a newly restructured redox background. In the end-Permian case, by contrast, Phase F is characterized less by one new energetic substrate than by ecological release of flexible, opportunistic, and generalist survivors under altered thermal, chemical, and circulatory constraints. Across the cases, Phase F shows what the new regime favors, whether pre-adaptation is visible, and how the generative half of BBRS differs from a purely collapse-centered account.

Seen through evolutionary theory, BBRS can be read as planetary-scale niche construction under delayed buffer failure: organisms, metabolisms, or institutions modify their environment through byproducts, the modified environment feeds back as a selective regime; and buffering allows the constructed niche to persist long enough to shape later vulnerability. The extension beyond standard niche-construction theory is scale and delay: the constructed niche can become planetary, and the selection it imposes may outlast the producer's local feedback environment (Odling-Smee, Laland, and Feldman, 2003).

A related expectation is adaptive commitment to buffered baselines. The more successfully Phase B filters the load, the more strongly selection can reward dependence on the filtered environment and suppress traits suited to the less-filtered one, a logic consistent with ecological and evolutionary trap theory. Phase E mortality is then the delayed cost of prior success under a baseline that buffering made temporarily real. The severity and selectivity of a BBRS should depend partly on how long and how completely the prior regime trained organisms, ecosystems, or institutions to inhabit conditions that buffer failure would later remove. In cyclic settings, partial recovery can deepen this commitment: repeated returns to the buffered baseline may reselect for dependence on conditions that each high-load phase is making harder to maintain. Candidate tests include calcification tolerance in reef builders, hypoxia or pH tolerance in planktonic communities, redox/substrate dependence in matground ecosystems, and thermal or hydrologic tolerance in forest and wetland systems. Buffer-edge environments aren’t just refugia; they are candidate selection environments for post-transition dominants, because their inhabitants experience a less-filtered version of the load before it becomes ambient (Schlaepfer et al., 2002). Accordingly, a Deceptive Stability Interval can become a stability trap: the same buffering that reduces near-term disruption can deepen dependence on the buffered baseline when load continues and slack is not restored.

Existing trait and distribution studies already provide partial tests of this expectation. Buffer-edge environments are not presumed to be successor regimes; they are candidate source environments where traits, assemblages, or functional strategies favored under weakening buffered baselines may already be concentrated.

Buffer-edge setting	**Published observation**	**BBRS interpretation**	**Candidate successor-regime expectation**
Thermally variable reefs	Studies of corals from thermally variable reef habitats in American Samoa found heat-resistant populations and showed that local acclimatization and fixed effects such as adaptation contributed to thermal tolerance; genomic work also found heat-associated alleles more common in warm microclimates (Palumbi et al., 2014; Barshis et al., 2013).	Thermally variable reefs are not only stressed outliers; they are candidate Phase B selection environments where organisms experience a less-filtered thermal load.	Heat-tolerant coral-symbiont combinations, stress-response genotypes, or altered calcification strategies should be overrepresented in environments already exposed to high thermal variance.
Naturally low-pH / low-carbonate-saturation reefs	Palau Rock Islands studies reported diverse coral-dominated communities under chronically low pH and aragonite saturation, while later work found community changes across Palau's natural pH gradient; other naturally low-pH systems show reef responses to acidification exposure (Shamberger et al., 2014; Barkley et al., 2015).	Naturally acidic reefs provide analogues for less-filtered carbonate stress, where Phase B communities are already exposed to conditions that may become more widespread.	Acidification-tolerant calcifiers, heterozoan or microbial carbonate modes, lower-accretion assemblages, or non-framework carbonate production should become more important as carbonate buffering weakens.
Upwelling-influenced reef systems	Upwelling systems expose reefs to cooler, nutrient-rich, CO2-rich, lower-pH waters; reviews and site studies link upwelling with altered reef community structure and naturally acidified conditions (Sánchez-Noguera et al., 2018; Enochs et al., 2021).	Upwelling reefs are buffer-edge environments for carbonate chemistry and temperature variability, not merely local anomalies.	Assemblages already tolerant of low pH, nutrient variability, and episodic stress should provide candidate predictors for post-threshold reef community structure.
Oxygen-variable coastal zones / OMZ margins	Oxygen minimum zones and hypoxic coastal systems host communities structured by low oxygen; reviews describe OMZ microbial ecology, and benthic studies show density and community responses across oxygen gradients (Breitburg et al., 2018; Wright et al., 2012).	Low-oxygen margins are candidate selection environments for organisms and metabolisms suited to deoxygenated successor conditions.	Hypoxia-tolerant taxa, microbial metabolisms, and benthic assemblages already operating near oxygen limits should become more important where oxygen buffering weakens.
High-disturbance forests and landscapes	Disturbance-legacies research shows prior disturbance can shape later forest resilience, while climate/disturbance	Recurrent disturbance environments expose communities to a less-filtered version of climatic and hydrologic	Drought-, fire-, heat-, or disturbance-tolerant functional types should be overrepresented among communities

Buffer-edge setting	Published observation	BBRS interpretation	Candidate successor-regime expectation
	reviews emphasize that changing disturbance regimes can reorganize ecosystems and biogeography (Johnstone et al., 2016; Seidl et al., 2017).	stress.	that persist as climatic buffering weakens.
Mangrove / wetland salinity and flooding gradients	Reviews of mangrove climate impacts emphasize regional variation in sea-level rise, salinity, flooding, and species responses; mangroves are inherently positioned along land-sea hydrologic gradients (Ward et al., 2016; Osland et al., 2022; Cavanaugh et al., 2014).	Wetland and mangrove ecotones are buffer-edge settings for hydrologic, salinity, sediment, and carbon-storage stress.	Salt- and flood-tolerant assemblages, altered carbon-storage functions, or migrating wetland/mangrove functional types should become more important as hydrologic buffering weakens.

Table 10. Published buffer-edge observations interpretable as BBRS tests of post-transition trait sources. These studies are not presented as proof that successor regimes have already formed. They show that existing trait, genomic, physiological, and distribution data can test whether less-filtered Phase B environments preferentially contain traits or assemblages favored under emerging successor conditions.

Byproduct valence splits Phase F into two different successor logics. In energetic succession, the accumulated byproduct becomes infrastructure for a higher-power or more expansive successor regime, as oxygen eventually did for aerobic metabolism (Kleidon, 2012). In tolerance succession, successor forms endure altered conditions without gaining a comparable energetic opportunity; survival depends on tolerance, migration, simplification, or external closure. This prevents GOE, end-Permian, PETM, and Anthropocene cases from being treated as equivalents simply because all involve buffered load and threshold response. Phase F depends on a race between slack exhaustion and the emergence or scaling of organisms, technologies, or geochemical pathways capable of closing the cycle that the buffer had temporarily carried.

The interaction between buffer status and byproduct valence clarifies why BBRS cases can share a phase grammar while leading to different successor regimes.

Buffer status	Byproduct valence	BBRS interpretation	Representative implication	Successor-regime consequence
High slack	Harvestable / exergy-positive	The byproduct is still partly hidden or spatially restricted, but it can create edge niches for future winners.	Microoxic or chemically variable environments can incubate lineages or metabolisms that later expand.	Pre-adapted forms may be present before ambient reorganization.
Low slack	Harvestable / exergy-positive	The byproduct becomes ambient and usable as a resource, electron acceptor, substrate, or enabling medium.	The GOE becomes not only oxygen toxicity, but buffered exergy accumulation; oxygen later becomes planetary energy infrastructure.	Energetic succession; waste becomes infrastructure for a higher-power regime.
High slack	Spent / exergy-negative	Buffers substitute for missing cycle closure while closure debt accumulates invisibly.	Anthropocene CO2 and heat can be hidden by land/ocean sinks and heat uptake while the industrial metabolism continues scaling.	Deceptive stability; intervention still possible if closure pathways are built before slack loss becomes dominant.
Low slack	Spent / exergy-negative	The load becomes ambient without providing a comparable successor energy opportunity.	End-Permian and Anthropocene-like stressors can tighten habitability constraints rather than create a new high-power medium for animals or institutions.	Tolerance succession, simplification, migration, collapse, technological closure requirement, or slow geochemical recovery.

Table 11. Buffer status and byproduct valence as a discriminator among BBRS successor regimes. The table does not replace the six-phase grammar; it clarifies why similar buffer-depletion sequences can produce different Phase F outcomes depending on whether the accumulated byproduct can be recruited into a successor cycle or remains a closure debt.

5.5 Diagnostic Consequences of Buffered Stability

Buffered stability changes what counts as evidence before threshold crossing. A functioning buffer can manufacture false negatives by absorbing load into reservoirs, sinks, living structures, or spatial heterogeneity outside the variables used to infer stability. Its deeper consequence is a calibration trap: the filtered baseline preserved during Phase B becomes the training environment for organisms, ecosystems, and institutions. Selection, adaptation, risk models, and institutional learning are tuned to the residual signal the buffer permits, not to the underlying load it absorbs. Phase B can spend two coupled reserves at once: material slack in the buffer and recognition capacity in systems calibrated to the buffered world. Success during Phase B can therefore become Phase E vulnerability; when visible failure arrives, the detecting system may already be tuned to the wrong baseline. Some slack loss is also structurally hidden because it is stored in reservoirs, sinks, spatial heterogeneity, incomplete recovery between cycles, or archive degradation before familiar observables respond. This unobserved residual capacity, or dark slack, can be spent without appearing directly in the variables used to infer stability. In some cases, buffering does not merely hide slack loss from observers; it suppresses or degrades the formation of the record by which that loss would later be reconstructed. In buffered transitions, quiet intervals in the archive may be quiet not because little is happening, but because buffering is still preventing load from entering the recorded signal environment. In the most difficult cases, the buffer erases or degrades the record through which its own failure would later be recognized, making structured absence part of the evidence rather than a gap.

BBRS makes a covariance prediction: process-coupled missingness should not be randomly distributed with respect to buffer stress. Proxy dropout, preservation loss, carbonate dissolution, or archival thinning should be spatially and temporally concentrated where inferred slack loss, pass-through, or buffer-edge stress is greatest. A failure to find such covariance in canonical cases would weaken the strong observability claim, even if a weaker slack-depletion reading remained possible. In buffered transitions, the quietest intervals in the archive may be quiet not because little is happening, but because buffering is still preventing load from entering the recorded signal environment. A BBRS should be evaluated by asking where stability is being produced, whether dark slack remains in the structures producing it, and whether the records used to recognize later failure are themselves being filtered or degraded.

The inferential shift is this: in standard threshold framing, the pre-threshold interval is often treated as the period before the event. In BBRS, that interval is part of the event's causal machinery. It suppresses warning, selects for dependence on a disappearing baseline, and can damage or fragment the evidence by which slack loss would later be reconstructed. Patchiness, proxy dropout, trait-selective stress, and persistent headline stability are not secondary complications; they are candidate expressions of the same buffered transition geometry.

6. Conclusion and Research Agenda

Across Earth history, some of the most consequential transitions have begun with the continued success of buffering systems that hide accumulating instability. BBRS identifies a recurring diagnostic architecture in such cases, where persistent byproduct loading is absorbed long enough to preserve apparent stability while the capacity producing that stability declines. It does not propose a new physical mechanism for oxygenation, extinction, hyperthermal warming, or Anthropocene change. It identifies a recurring causal architecture that becomes hard to see when these cases remain confined to separate literatures: persistent byproduct loading, buffer-produced apparent stability, slack depletion, altered observable pass-through, selective vulnerability to the loss of a filtered baseline, and successor regimes shaped by the valence of accumulated residue. The contribution lies in the ordering. Stability becomes a question rather than a reassurance: which buffer is producing it, how much slack remains, and what follows when that filtering function weakens?

The GOE provides the canonical anchor; the end-Permian crisis fits as a compound case; the Ediacaran–Cambrian transition remains a candidate hypothesis program; and the Anthropocene is an application in which the variables are measured directly but trajectories are reflexive and policy contingent.

The framework’s strongest practical implication is that stability under persistent net load can be an unsafe guide when it is produced by active buffering whose cost must be accounted for: when organisms, institutions, and risk systems are calibrated to headline variables based on buffered residuals, the effective intervention window may narrow before those variables show commensurate deterioration. The central question is whether persistence reflects genuine safety or the expenditure of stabilizing capacity by the structures producing it.

6.1 Research Agenda

The strongest tests of BBRS will come from the pre-reorganization sequence. Four predictions are especially discriminating. First, observable pass-through should increase as buffer efficiency declines; state-variable acceleration should sometimes exceed source acceleration. Second, archive degradation or proxy dropout should be spatially and temporally structured by buffer stress instead of randomly distributed. Third, buffer-edge environments should disproportionately contain traits, metabolisms, or ecological strategies later favored under the successor regime. Fourth, repeated forcing cycles should become BBRS-relevant only when recovery phases fail to restore slack, producing cumulative margin loss rather than simple oscillation. These predictions are modest enough to test and specific enough to separate BBRS from the general observation that systems can tip.

1. Design slack-centered monitoring architectures. Future work should distinguish buffer output from buffer capacity. A valid BBRS monitoring strategy should pair each headline observable with its forcing term and an independent measure of buffer condition, so that acceleration in the observable can be decomposed into source acceleration versus declining pass-through suppression. For the Anthropocene, this means tracking not only atmospheric CO_2, temperature, pH, sea-ice extent, or biodiversity state, but also the capacity metrics that make those observables lag: sink efficiency, alkalinity and carbonate-state reserves, ocean heat uptake structure, forest and soil carbon integrity, reef accretion balance, circulation-density gradients, and institutional deployment capacity. In coupled-buffer systems, divergence among buffer-performance metrics may be more diagnostic than the mean of any single metric, because compensatory redistribution can preserve aggregate stability while slack becomes increasingly uneven.Test failure-mode classification. For each candidate BBRS system, determine whether buffering behaves more like gradual saturation or threshold collapse, using proxy resolution and model constraints.
2. Extend negative-control testing. Apply the signature checklist not only to additional candidate BBRS cases but also to explicit negative controls, including K-Pg. In the K-Pg case specifically, future work should test for evidence of meaningful pre-impact buffer depletion in relevant sedimentary and geochemical records; failure to find such a signal would sharpen the framework’s discriminative logic by showing that abrupt ecological turnover alone is insufficient for BBRS classification (Alvarez et al., 1980; Schulte et al., 2010).
3. Pursue coupled-buffer modeling. Extend BBRS from a scalar slack variable to vector-valued buffering systems with coupling terms, particularly for Anthropocene applications where ocean heat uptake, carbonate chemistry, land uptake, cryosphere change, and circulation structure may fail asynchronously and interactively.
4. Estimate intervention-window closure. Develop subsystem-specific methods for estimating closure of the effective intervention window, with explicit distinction between Type I and Type II buffers and with attention to τ_I, the institutional or technological deployment timescale required to reduce F, enhance R, or preserve B. In reflexive systems, intervention-window closure can be approximated by comparing τ_I with the remaining slack-lifetime, $\Sigma(t)/|d\Sigma/dt|$, and with the rate at which forcing is increasing relative to response capacity.
5. Use hyperthermal sequences as rate- and recovery-sensitivity comparators. The PETM is a particularly important comparator for BBRS testing because it combines rapid carbon injection, carbonate-buffer stress, and climate-ocean reorganization on timescales more directly relevant to

Anthropocene carbon-loading comparisons than the deeper canonical cases (McInerney & Wing, 2011; Zeebe et al., 2016). In rate terms, this comparison matters because the Anthropocene likely represents a more extreme forcing-rate challenge to buffering than PETM-scale carbon release, sharpening BBRS's claim that the relation between τ_F and τ_R is central to threshold risk. PETM-style hyperthermal sequences may also be useful test beds for distinguishing isolated forcing pulses from cumulative buffer-margin loss across repeated events. More broadly, repeated hyperthermals and other slow boundary-condition cycles may help test whether BBRS transitions reflect isolated forcing pulses or cumulative loss of buffer margin across recurrent events (Westerhold et al., 2020).

6. Classify BBRS outcomes by byproduct valence and closure pathway. Across candidate cases, test whether Phase F is better described as energetic succession, tolerance succession, or closure-dependent recovery. The GOE should behave as the canonical harvestable-byproduct case; PETM-style hyperthermals should behave mainly as geological closure tests; the Anthropocene should be evaluated as a reflexive technological closure test in which external non-fossil energy must re-close cycles that fossil-energy metabolism opened faster than biospheric or geochemical buffers can absorb.
7. Reinterpret existing monitoring datasets as pass-through diagnostics. Published records of airborne fraction, land and ocean sink efficiency, ocean heat uptake, Earth energy imbalance, carbonate saturation, reef carbonate production, circulation resilience indicators, source/sink divergence, and paired deep-time proxy families already contain partial BBRS diagnostics. The immediate task is to test whether these records show increasing observable pass-through, incomplete recovery, or spatially structured buffer weakening before familiar state variables fully register reorganization.
8. Test Anthropocene carbonate-factory shifts as living-buffer failure. Modern reef systems offer a tractable test of whether BBRS dynamics can be detected as a sedimentological transition before complete ecological collapse. Future work could compare pre-industrial, pre-1980, and post-1980 intervals in well-dated shallow-marine reef cores, point-counting skeletal and non-skeletal grains to test whether degraded tropical systems are shifting away from coralgal carbonate production toward heterozoan, microbial, or lower-accretion assemblages. Such a test would connect ecological reef phase shifts, carbonate-budget decline, and deep-time carbonate-factory transitions within a single BBRS diagnostic: whether a living carbonate buffer records slack loss first as altered production mode rather than as immediate disappearance of the reef framework (Shaw et al., 2015; Cornwall et al., 2021; Reverter et al., 2022; Li et al., 2023).
9. Evaluate early-warning suppression under archive or observation-channel degradation. Future work should examine how proxy resolution, temporal averaging, stratigraphic smoothing, and preservation failure obscure or distort early-warning structure during Deceptive Stability Intervals, especially in candidate deep-time cases where what appears to be a stable Phase B may partly be a resolution artifact rather than true resilience. In some BBRS settings, independent indicators of buffer stress may intensify while headline observables or standard early-warning metrics remain muted, noisy, discontinuous, or degraded because the same process that depletes slack also damages the archive, sensor, or signal pathway. High-resolution paleoenvironmental archives, including tree rings, corals, speleothems, ice cores, and annually laminated sediments, may be especially useful for testing whether late Phase C first appears as rising spatial variance, source/sink sign reversal, or clustered local failure before a mean-state transition is evident (National Academies of Sciences, Engineering, and Medicine, 2026). In some cases, proxy dropout should not be treated only as missing data or taphonomic bias. A buffer can fail materially by losing the capacity to absorb load and epistemically by degrading the archive through which that failure would later be recognized; structured missingness, preservation loss, or proxy degradation may mark the geography of slack depletion, not just the limits of reconstruction. Carbonate dissolution, poor fossil preservation, redox overprinting, or archive loss may be process-coupled evidence that the relevant buffer was failing most strongly where the record becomes hardest to read. The key question is whether archive degradation has spatial and

temporal structure predicted by the stressor, rather than random absence.

10. Test observability covariance in canonical and compound BBRS cases. If buffering is a signal-filtering operation, proxy dropout, preservation loss, carbonate dissolution, archival thinning, or reduced early-warning expression should co-vary with independent indicators of buffer stress rather than appearing as random sampling loss. The end-Permian is a strong first test because basin-scale differences in redox state, carbonate preservation, and extinction timing can be compared against the predicted geography of slack loss. A null result would not falsify BBRS as a slack-depletion framework, but it would weaken the stronger claim that buffered transitions are self-obscuring in a structured way.

6.2 Reflexive-Producer Question

In the Anthropocene, the problem becomes one of timing and recognition. Unlike prior BBRS cases, the Anthropocene is the first in which the entity generating F(t) can also observe the degradation of $\Sigma(t)$ in real time and potentially act on that knowledge before threshold crossing becomes irreversible. Yet reflexivity does not eliminate the Phase B problem; it can internalize it. Monitoring systems may increasingly detect hidden slack loss with high fidelity, but the institutions that assign urgency to those signals were largely built under the buffered normalcy of the Deceptive Stability Interval itself. Policy thresholds, risk tolerances, economic baselines, and practical definitions of dangerous change are therefore not neutral reference points standing outside the buffering architecture; they are historical products of the interval whose filtered stability they now attempt to interpret. The result is a second-order lag between measurement and response: instruments may register deterioration earlier than institutions are structured to treat it as requiring emergency reorganization. Accordingly, the effective intervention window is not only a biophysical quantity set by remaining slack, subsystem reversibility, and failure mode; it is also an institutional quantity shaped by how rapidly response thresholds can be revised once buffered persistence is recognized as a lagging rather than reassuring signal. Such pre-adaptation would mean not passive endurance of altered baselines but deliberate reorganization of flux, removal, buffering, and institutional timing before threshold closure makes those adjustments primarily reactive rather than system-preserving. In a coupled buffering architecture, that challenge is sharper than a scalar formulation implies: reflexive action must respond not only to total load, but to uneven slack loss across linked subsystems whose failures can propagate. The Anthropocene question is whether a reflexive producer can recognize which buffers are failing, on what timescales, and before local deterioration is redistributed into broader regime change.

In such a case, the most dangerous and consequential failure is mistaking persistence for safety. A reflexive producer may possess abundant observations and still mistake buffered residuals for system safety or read regional fragmentation as local exception rather than early-phase propagation. This implies that buffering does not merely delay transition; it can manufacture an experienced normality that becomes progressively less truthful as the system spends the very slack that sustains it. BBRS frames the Anthropocene problem on those terms: forcing is part of the diagnosis, but so is interpretation under active signal filtering.

Can a reflexive producer become pre-adapted to its own waste medium before the transition eliminates that possibility?

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Appendix A. Formal Structure and Diagnostic Extensions

This appendix provides the minimal formalism underlying BBRS. The purpose of the sketch below is to stabilize the framework's variables and clarify the conditions under which BBRS claims would become testable or falsifiable. The equations are included to clarify variable relations, constrain the vocabulary of future quantitative work, and stabilize how terms such as load, buffering, threshold, and slack are used across cases. They are not presented here as a calibrated Earth system model for heterogeneous deep-time cases.

Conceptual falsification conditions are specified in the main text through the BBRS signature checklist and negative-control discriminator; the appendix formalism clarifies variable structure rather than serving as the primary falsification device.

Let E(t) represent an effective byproduct load or a downstream consequence measure that governs habitability partitions. Define F(t) as the flux of byproduct load into the system; R(t) as removal, sequestration, or neutralization; B(t) as effective buffering capacity; T as a threshold in E or in an associated control variable at which baseline reorganization occurs; B_{crit} as the buffering capacity below which the regime loses resilience; and $\Sigma(t) = B(t) - B_{crit}$ as buffer slack.

Let O(t) denote an observed state variable and let p(Σ) represent pass-through from the underlying load state E(t) into the observable domain. A minimal observation relation is $O(t) = Obase + p(\Sigma)E(t) + \varepsilon(t)$, where $0 \leq p(\Sigma) \leq 1$ and $\frac{\mathrm{dp}}{\mathrm{d}\Sigma} < 0$. When slack is high, pass-through is suppressed; as slack declines, a larger share of the same load becomes observable. In Type II buffering, p(Σ) may remain low until threshold proximity, suppressing variance and other early-warning statistics in O(t) even as risk increases as $\Sigma(t)$ declines. The point is not to provide a calibrated information-theoretic proof, but to state the observability problem: early-warning methods operating only on O(t) can miss risk stored in declining slack.

Differentiating the schematic observation equation clarifies why observable acceleration need not imply source acceleration alone. If $O(t) = O_{base} + p(\Sigma(t))E(t) + \varepsilon(t)$, then $dO/dt = p(\Sigma)dE/dt + E(t)(dp/d\Sigma)(d\Sigma/dt) + d\varepsilon/dt$. Because dp/d\Sigma<0 and d\Sigma/dt<0 during slack depletion, the second term can amplify the observable response even when dE/dt is not increasing. This is the formal counterpart of the pass-through diagnostic in the main text: acceleration in O(t) can reflect declining buffer efficiency as well as increasing source load.

A further distinction is needed between physical pass-through and observation-channel integrity. If p(Σ) denotes the fraction of accumulated load expressed in the observable domain, then $p'(\Sigma) < 0$: pass-through increases as slack declines. But the archive or monitoring substrate may degrade at the same time. This can be represented by an observation-channel term A(Σ)), where $A'(\Sigma) > 0$ and declining slack reduces archive completeness, proxy continuity, or signal reliability. A schematic measured record can therefore be written as $Y(t) = A(\Sigma(t))[O_{base} + p(\Sigma(t))\,E(t)] + \varepsilon(t,\Sigma)$. In such cases, physical pass-through and inferential quality move in opposite directions: the system may become more stressed while the record becomes less reliable. Carbonate dissolution, redox overprinting, ice loss, reef-framework degradation, or ecological archive loss can therefore reduce inferential quality in the same intervals where physical pass-through is increasing. In such cases, archive degradation is BBRS-relevant only when it covaries with independently inferred buffer stress.

In reflexive or producer-coupled systems, F(t) need not be wholly exogenous. Where buffering suppresses immediate negative feedback to the producer, forcing can depend on the visibility of its own costs: $\frac{\mathrm{dF}}{\mathrm{dt}} = G(F,t) - C(O)F$, with $O(t) = Obase + p(\Sigma)E(t) + \varepsilon(t)$. High slack can lower O(t), reducing the cost-feedback term and allowing load generation to scale. This formalizes buffer-subsidized forcing in the Anthropocene and other producer-coupled cases without making endogenous F(t) a requirement for all BBRS examples.

BBRS depends not only on cumulative net load but on the relation between forcing timescale and buffer replenishment or recovery timescale. Let τ_F denote the characteristic timescale of forcing and τ_R the characteristic timescale over which buffering is restored, regenerated, or redistributed. For reflexive systems, especially the Anthropocene application, a third timescale is also useful: τ_I, the institutional or technological deployment timescale required to reduce F, enhance R, or preserve and restore B. The effective intervention window narrows when τ_I approaches or exceeds the remaining slack-lifetime, approximated schematically as $\frac{\Sigma(t)}{|d\Sigma/dt|}$, or when response deployment is slower than the rate at which forcing is increasing. This does not define a universal threshold, but it clarifies why visible deterioration can arrive after system-preserving intervention has become difficult or impossible. A given cumulative load may remain bufferable when $\tau_F \gg \tau_R$, but the same load can drive thresholded reorganization when $\tau_F \ll \tau_R$. In this sense, BBRS is sensitive not only to the magnitude of net accumulation but to the mismatch between delivery rate and replenishment rate.

Slack can also be read as a memory variable. Where recovery is slow relative to forcing, $\Sigma(t)$ approximates the cumulative history of unresolved net loading; where recovery is faster, the system partially forgets past loading through replenishment or redistribution. More generally, slack could be represented with a recovery kernel, so that past net load contributes to current slack in proportion to how slowly the relevant buffer restores. This memory interpretation is why cyclic forcing becomes BBRS-relevant only when low-load phases fail to restore the slack lost during high-load phases.

$$\frac{dE}{dt} = F(t) - R(t)$$

$$\frac{dB}{dt} = -\alpha \max(0, F - R) + \beta G(t)$$

In the limiting case of negligible recovery and approximately constant buffer-consumption efficiency, these equations imply a simple budget relation between accumulated load and remaining slack: $E + \Sigma / \alpha \approx E_0 + \Sigma_0 / \alpha$. Under constant positive net load, the remaining slack-lifetime can be approximated as $\Sigma(t) / [\alpha (F - R)]$. These expressions are not intended as calibrated predictors; they clarify the ratio geometry of BBRS by showing why the effective intervention window narrows as positive net load persists while slack declines.

The coefficients in this expression should be read as schematic rather than constant. In reactive or structurally degrading buffers, buffer consumption may be state-dependent, so $\alpha = \alpha(E, \Sigma)$. This allows chemical, ecological, or circulation-mediated buffering to weaken nonlinearly as load accumulates or slack declines. Similarly, regeneration or reinforcement may depend on buffer condition, so G(t) may be written more generally as G(t,B) where living, geochemical, or institutional buffering becomes less able to regenerate as B approaches $B_{critical}$. The simplified form is retained only to stabilize notation across heterogeneous cases.

Future formal work could express these relations as dimensionless load-to-slack and response-to-forcing ratios, but the present paper retains the variables schematically because the relevant buffers are heterogeneous and not directly commensurable across cases.

Apparent stability during Phase B can be represented by an observable response variable, O(t), whose sensitivity to E(t) is damped while $\Sigma(t)$ remains positive; as $\Sigma(t)$ declines, the same increment of E(t) produces a larger observable response.

The distinctive comparative move is not the balance equation itself, which is established in source–sink reasoning, but the elevation of $\Sigma(t)$ as the hidden control variable governing nonlinear susceptibility. In conceptual terms, Phase B corresponds to positive slack large enough that E remains below threshold or that critical baseline structure persists; Phase C corresponds to declining Σ as buffers are consumed or structurally weakened; Phase D corresponds to crossing a regime boundary associated with E or with a related control variable.

Type I buffers can be sketched as continuous decline in B with cumulative net load; Type II buffers can be sketched as structural or metastable regimes in which B remains functionally high until a boundary condition is crossed, after which buffering declines rapidly. Early warning in Type II systems may appear as rising heterogeneity, slowing recovery, or patchiness rather than smooth drift.

A minimal coupled-buffer extension allows deterioration in one buffer to increase effective load on another. In schematic form, one may write $\frac{dB_2}{dt} = -\alpha_2 \max\{0, F(t) - R(t)\} - \gamma \max\{0, B_{1,crit} - B_1(t)\} + \beta_2 G_2(t)$. Here, $\alpha_2, \beta_2, \gamma > 0$, and *G(t)* or $G_2(t)$ represents buffer regeneration, reinforcement, or redistribution, where $\gamma > 0$ captures cross buffer stress transfer once buffer 1 enters or crosses its critical range; the max $(0, B_{1,crit} - B_1)$ term is a schematic post-critical shorthand, since real systems may begin redistributing stress as B_1 approaches $B_{1,crit}$, not only after it falls below it. The threshold form of the coupling term is a limiting case. In many real systems, stress transfer may begin before B_1 crosses $B_{1,crit}$, and the coupling term could be replaced by a smooth function γ f($B_1/B_{1,crit}$) that increases as B_1 weakens. The max function is retained here only as a compact way to represent threshold-dominated transfer. This is not yet a calibrated network model, but it makes explicit how slack loss in one subsystem can accelerate slack depletion in another.

Appendix B. Per-case Variable Operationalization Tables

The following tables translate BBRS variables into case-specific proxy families and observational handles. They are schematic, not calibrated, and show how source terms, buffering structures, slack indicators, pass-through signals, spatial divergence, archive quality, and successor-regime outcomes can be recognized differently across cases.

B1. Great Oxidation Event

BBRS variable	GOE interpretation	Illustrative proxy families
F(t)	Effective O_2 production and burial-driven net oxygen source	Organic burial context, isotopic and redox proxies
R(t)	Reductant sinks consuming O_2	Reduced mineral transport, sulfur and iron sink indicators
B(t)	Integrated redox buffering structure	Iron/sulfur cycling structures, sink reservoir proxies
$\Sigma(t)$	Remaining slack in reductant sinks/ buffering structure	Inferred from evolving sink dominance and convergence of proxy transitions
T	Atmospheric chemistry/redox threshold	Sulfur MIF disappearance and related atmospheric redox indicators
Pass-through / spatial divergence / archive quality / successor outcome	As reductant sinks lost dominance, a larger fraction of biological O_2 production passed through into atmospheric and oceanic redox expression. Oxygenation was spatially and temporally uneven rather than globally instantaneous. The successor regime was exergy-positive: O_2 shifted from toxic byproduct to planetary electron-acceptor infrastructure for aerobic metabolism.	Sulfur MIF disappearance, iron-formation and red-bed patterns, redox-sensitive trace-metal proxies, sulfur and carbon isotope transitions, spatially uneven marine oxygenation indicators, fossil/metabolic evidence for aerobic expansion.

B2. End-Permian Crisis

BBRS variable	End-Permian interpretation	Illustrative evidence
F(t)	Sustained volcanogenic forcing plus coupled stress load	Large igneous province timing and climate proxies
R(t)	Removal via carbonate buffering, ventilation, ecosystem processing	Carbonate-system and circulation-capacity evidence
B(t)	Buffering structures: carbonate chemistry plus ventilation capacity	Redox proxies, ventilation indicators, ocean-structure evidence
$\Sigma(t)$	Remaining slack in ventilation and buffering	Expansion of anoxia/euxinia and worsening redox conditions

T	Circulation/redox threshold	Rapid transition to widespread oxygen loss and ecological collapse
Pass-through / spatial divergence / archive quality /successor outcome	As carbonate, ventilation, and ecological buffering weakened, more of the volcanogenic stress load appeared as warming, acidification, hypoxia/anoxia, euxinia, and ecological collapse. Slack loss was spatially uneven across basins and shelves. Archive quality may decline where dissolution, redox overprinting, condensation, or ecological collapse are strongest. The successor regime is largely tolerance succession rather than energetic succession for complex aerobic life.	Carbon-isotope excursions, carbonate dissolution and compensation evidence, redox proxies, pyrite framboids, Mo/U and Fe-speciation patterns, basin-scale ventilation gradients, fossil selectivity, microbialite expansion, preservation gaps or facies changes near crisis intervals.

B3. Anthropocene Carbon Era

BBRS variable	Anthropocene interpretation	Illustrative observational handles
F(t)	CO_2 emissions and land-use forcing	Emissions inventories, effective radiative forcing
R(t)	Land and ocean uptake pathways	Observed partitioning of anthropogenic CO_2
B(t)	Buffering structures: ocean heat uptake, carbonate chemistry, sink integrity	Ocean heat content, saturation state, ecosystem-resilience indicators
Σ(t)	Remaining buffering slack and sink effectiveness	Sink-efficiency trends, commitment metrics, resilience proxies
T	Subsystem thresholds or tipping risks	Assessed subsystem thresholds and nonlinear-risk literature
Pass-through / spatial divergence / archive quality / successor outcome	As carbon, heat, carbonate-chemistry, cryosphere, and biospheric buffers weaken or redistribute load, more forcing becomes visible in atmospheric CO_2 retention, ocean heat storage, acidification, ecological stress, and regional extremes. Phase C should appear as spatial divergence among subsystem buffers and incomplete recovery between events. Archive quality and monitoring continuity may degrade where reefs, ice, permafrost, and biological records are being altered by the same forcing they record. The successor outcome is closure-dependent: CO_2 and heat are spent byproducts requiring external work, technological closure, or slow geochemical return.	Airborne fraction, land/ocean sink efficiency, Earth energy imbalance, ocean heat content, carbonate saturation and pH, regional acidification maps, reef accretion and bioerosion, ice/permafrost archive loss, ecological recovery metrics, circulation indicators, infrastructure and monitoring-continuity records.

Appendix C. Case-Level Diagnostic Matrices for BBRS

C.1 Purpose and use

This appendix makes the BBRS grammar operational at case level. It is not meant to prove that every comparison is equally strong. It shows how the same diagnostic sequence can be walked through while preserving differences in evidentiary strength, buffer architecture, byproduct valence, and closure potential.

A strong BBRS reading depends on evidentiary ordering rather than checklist presence alone: sustained load; identifiable sink or buffer mediation; declining buffer performance, incomplete recovery, spatial fragmentation, rising observable pass-through, or archive attenuation before or during reorganization; thresholded background-state change; selective vulnerability linked to dependence on the buffered baseline; and a successor regime whose character depends partly on whether the accumulated byproduct can be recruited into a new cycle or remains closure debt.

The matrices also separate three questions that can otherwise blur together: (1) Did buffering delay expression of the load? (2) Did slack loss alter observability, selection, or archive quality before threshold crossing? (3) Did the byproduct become usable infrastructure for the successor regime, or did it remain a constraint requiring external work or slow geochemical closure?

C.2 Cross-case diagnostic overview

Case	BBRS status	Dominant load and producer	Principal buffering architecture	Phase C diagnostic geometry	Byproduct valence and closure outcome	What would weaken the BBRS reading
Great Oxidation Event	Canonical case	Biogenic O2 production by oxygenic photosynthesis; persistent oxygen source initially held below persistent atmospheric expression.	Reduced iron, sulfur, volcanic/metamorphic gases, crustal reductants, and ocean-atmosphere redox sinks.	Increasing oxygen pass-through as reductant sinks lose capacity; stepwise or intermittent oxygenation; spatially heterogeneous redox transition; eventual atmospheric expression.	Harvestable / exergy-positive byproduct. O2 was toxic waste for anaerobic systems, then became high-value electron-acceptor infrastructure for aerobic metabolism. Phase F is energetic succession.	Evidence that atmospheric oxygenation was not sink-mediated, or that O2 accumulation had no meaningful relation to reductant-buffer exhaustion, would weaken canonical status.
End-Permian crisis	Compound BBRS case	Carbon release, heat, acidification, stratification, hypoxia/anoxia, euxinia, and ecological disruption associated with Siberian Traps forcing and coupled Earth system feedbacks.	Carbonate chemistry, ocean ventilation, oxygen solubility, biological pumps, ecosystem structure, and redox buffers.	Spatially uneven anoxia/euxinia, carbonate stress, extinction selectivity, basin heterogeneity, and possible archive degradation in the most stressed settings.	Mostly spent / closure-demanding byproducts for complex aerobic life. CO2, heat, acidification, and oxygen loss reorganize habitability without providing animals a new high-power medium analogous to O2.	If deterioration lacks a sustained pre-threshold buffer-strain sequence, or if selectivity is better explained by a short shock independent of prior slack depletion, the BBRS reading weakens.

Table C1a. Cross-case diagnostic overview, canonical and compound cases.

Case	BBRS status	Dominant load and producer	Principal buffering architecture	Phase C diagnostic geometry	Byproduct valence and closure outcome	What would weaken the BBRS reading
PETM and hyperthermal sequences	Rate- and recovery-sensitivity comparator	Rapid carbon injection, warming, carbonate-buffer stress, and ocean chemistry reorganization.	Ocean carbonate compensation, silicate weathering feedbacks, biological carbon cycling, and sedimentary carbonate reservoirs.	CCD shoaling/recovery, carbonate dissolution, temperature response, biotic redistribution, and recovery over geologic rather than institutional timescales.	Spent / closure-demanding byproduct. Carbon release is eventually reclosed largely through geochemical compensation and burial, not by CO2 becoming a new high-power substrate for complex animals or industrial society.	If hyperthermals behave as isolated pulses without cumulative margin loss, incomplete recovery, or rate sensitivity, they remain comparators rather than BBRS exemplars.
Anthropocene	Ongoing application	Synchronized human forcing: fossil-carbon release, heat, land transformation, nitrogen/phosphorus mobilization, material throughput, and biodiversity pressure.	Ocean heat uptake, land and ocean carbon sinks, carbonate chemistry, cryosphere/albedo, circulation, forests, soils, wetlands, reefs, and institutions.	Increasing observable pass-through, regional divergence, incomplete recovery between extremes, source/sink divergence, buffer-edge stress, and institutional warning lag.	Spent / closure-demanding byproducts with reflexive possibility. CO2 and heat are largely products of high-power metabolism/combustion; closure requires external non-fossil energy, biological uptake, geochemical storage, or technological intervention.	If human forcing falls below recovery capacity and buffers restore slack faster than pass-through increases, the Anthropocene remains a high-stress application rather than a completed BBRS.

Table C1b. Cross-case diagnostic overview, comparator and Anthropocene application cases.

Case	BBRS status	Dominant load and producer	Principal buffering architecture	Phase C diagnostic geometry	Byproduct valence and closure outcome	What would weaken the BBRS reading
Ediacaran-Cambrian transition	Candidate / hypothesis program	Potential disruption of matground-dominated substrates, microenvironmental redox structuring, ecological engineering, and oxygen/substrate feedbacks.	Microbial mats, sediment stabilization, redox microhabitats, substrate chemistry, and early ecosystem engineering.	Predicted weakening of matground buffering before full substrate revolution; trace/fossil/ecological evidence should show ordering from buffer disruption to ecological release.	Uncertain. Possible tolerance/ecological-succession case rather than exergy-positive byproduct revolution. More work needed to identify the load-buffer pair.	Absent the ordering from matground/redox-buffer weakening to ecological release, the interval should remain a comparison case rather than a BBRS member.
K-Pg boundary	Negative control / mixed press-pulse boundary test	Acute Chicxulub impact with temporally associated Deccan volcanism; severe consequences but not primarily defined by a demonstrated Deceptive Stability Interval.	Not a BBRS-style finite sink substituting for missing cycle closure before the main transition, unless a separate volcanic press component is specified and evidenced.	Discrete event marker and abrupt forcing dominate the boundary signal; any press-pulse complexity must be separated from BBRS membership.	Not a byproduct-valence case in the BBRS sense. Consequences are enormous, but abrupt shock alone does not establish cycle-closure debt or sink-mediated lag.	If sustained pre-boundary loading plus declining slack can be shown to organize the main transition more than acute shock forcing, the case would move from negative control toward mixed press-pulse comparison.

Table C1c. Cross-case diagnostic overview, candidate and boundary-testing cases. Abrupt ecological consequence is not sufficient unless the transition is organized by sustained load, buffer-mediated lag, slack depletion, and ordered reorganization.

C.3 Phase-level matrices

The following matrices preserve the A-F grammar while adding the v5 diagnostics: observable pass-through, Phase C spatial/temporal geometry, adaptive commitment, archival attenuation, and byproduct valence. They are intended to replace sparse one-sentence phase maps with case-level diagnostic structure.

C.3.1 Great Oxidation Event: canonical exergy-positive BBRS

Phase	Case expression	Diagnostic evidence / expectation	Constraint, uncertainty, or falsification handle
A. Load emergence	Oxygenic photosynthesis produces O2 as a persistent byproduct, initially decoupled from stable atmospheric accumulation by abundant reductant sinks.	Evidence should emphasize source-sink imbalance: oxygen production exists before persistent atmospheric expression.	If oxygen production and atmospheric oxygenation were synchronous without major sink mediation, the DSI interpretation weakens.
B. Deceptive Stability Interval	Reductant reservoirs absorb O2, keeping the experienced atmospheric/oceanic redox baseline partly buffered despite ongoing production.	Stable or intermittent redox proxies should be read as buffered residuals, not absence of O2 production.	Proxy resolution and local redox heterogeneity may blur the timing of source growth versus sink exhaustion.
C. Slack depletion	Reductant capacity becomes increasingly unable to absorb the O2 source; more O2 passes through into ocean-atmosphere observables.	Expected signatures include stepwise oxygenation, redox heterogeneity, changing sulfur/iron behavior, and spatially variable pass-through.	A purely external forcing explanation without reductant-buffer exhaustion would weaken canonical status.
D. Threshold crossing	Atmospheric/oceanic redox baseline reorganizes once O2 pass-through becomes persistent enough to alter background conditions.	A threshold should appear as persistent atmospheric oxygenation rather than merely local or transient oxidative events.	The exact threshold may be time-transgressive and cannot be reduced to a single global instant.
E. Selective vulnerability	Anaerobic or low-oxygen-adapted strategies face a changing baseline; prior success under buffered reducing conditions becomes vulnerability.	Selective stress should track dependence on the prior redox baseline and inability to exploit oxygenated conditions.	Microbial/ecological records are indirect and may not resolve trait-level selectivity cleanly.
F. Successor regime	O2 becomes planetary energy infrastructure as aerobic respiration recruits the former waste as a terminal electron acceptor.	This is energetic succession: waste becomes power, not merely tolerated constraint.	The timing between oxygenation and full aerobic ecological expansion may be lagged and ecologically complex.

Table C2. GOE phase-level diagnostic matrix. The GOE is treated as canonical because the byproduct is both buffered load and later energetic infrastructure.

C.3.2 End-Permian crisis: compound buffer failure and tolerance succession

Phase	Case expression	Diagnostic evidence / expectation	Constraint, uncertainty, or falsification handle
A. Load emergence	Carbon release and associated warming, acidification, oxygen loss, stratification, euxinia, and ecological disruption accumulate as a compound load.	The case should be reconstructed as multiple coupled forcing pathways rather than one scalar stressor.	Over-attribution to any single kill mechanism risks flattening the compound BBRS structure.
B. Deceptive Stability Interval	Marine and terrestrial systems may retain partial structure while carbonate chemistry, ventilation, oxygen availability, and ecosystem buffers absorb or redistribute stress.	Persistence of some ecological or sedimentary patterns should be tested against hidden buffer expenditure and regional heterogeneity.	The timing and completeness of pre-threshold stability vary by basin, habitat, and proxy type.
C. Slack depletion	Buffer strain appears as spatial patchiness: uneven carbonate stress, oxygen loss, redox instability, ecological fragmentation, and possible preservation loss.	Phase C should show basin-level divergence and increasing pass-through from forcing to observable stress.	Sparse preservation can be both evidence and limitation; structured missingness matters only if it tracks inferred buffer stress.
D. Threshold crossing	Background environmental state reorganizes into conditions incompatible with many prior-regime specialists.	Threshold should be visible as converging evidence of climate-ocean-redox/ecological reorganization, not only taxonomic turnover.	Multiple pulses may complicate the phase boundary.
E. Selective vulnerability	Specialists calibrated to oxygenated, stable, carbonate-building, or narrowly buffered conditions suffer disproportionate vulnerability.	Selectivity should track dependence on prior buffered conditions, physiological tolerance, habitat structure, and food-web position.	A purely random extinction pattern would weaken the adaptive-commitment interpretation.
F. Successor	Recovery favors opportunists, microbial/geochemical	This is mostly tolerance succession and ecological triage;	The eventual Mesozoic recovery is real but does

regime	modes, tolerant lineages, and reorganized ecosystems rather than a new high-power medium for animals.	the byproducts tighten constraints instead of becoming animal energy infrastructure.	not make CO2/heat an analogue to O2 as exergy-positive waste.

Table C3. End-Permian phase-level diagnostic matrix. The case is compound because multiple buffers and stress pathways interact rather than one byproduct-buffer pair acting alone.

C.3.3 PETM and hyperthermals: rate, recovery, and closure timescale comparator

Phase	Case expression	Diagnostic evidence / expectation	Constraint, uncertainty, or falsification handle
A. Load emergence	Rapid carbon addition imposes a climate-carbonate-chemistry load.	The key diagnostic is rate relative to carbonate compensation and longer weathering/burial recovery timescales.	The source magnitude and rate carry substantial uncertainty.
B. Deceptive Stability Interval	Carbonate and ocean buffers absorb part of the load, muting immediate atmospheric/ocean response relative to total perturbation.	Early response should be read as filtered by carbonate buffering and ocean partitioning.	The PETM may not have a long DSI comparable to GOE; its value is comparative, not canonical.
C. Slack depletion	Carbonate dissolution, CCD shoaling, ocean acidification stress, warming, and biotic redistribution indicate buffer strain.	Pass-through can be tested by comparing inferred carbon input against carbonate, isotopic, temperature, and biotic response.	Proxy preservation and dating uncertainty limit resolution.
D. Threshold or excursion peak	The system reaches a reorganized hyperthermal state with major climate and ocean-chemistry effects.	The crossing is less a permanent regime shift than a strong perturbation that reveals rate sensitivity and recovery constraints.	The PETM should not be overtreated as a mass-extinction analogue.
E. Selective vulnerability	Biotic effects reflect tolerance, migration, dwarfing, turnover, and ecosystem redistribution under carbon-cycle and thermal stress.	Selectivity should be tied to thermal, carbonate, trophic, and habitat dependence, not only carbon magnitude.	The selectivity structure is less catastrophic than end-Permian, making the case a comparator.
F. Recovery / closure	Geochemical recovery occurs through carbonate compensation, silicate weathering, burial, and long-timescale carbon-cycle reclosure.	The key lesson is closure timescale: recovery can occur, but too slowly for human institutional planning.	A recovery pathway exists geologically; that does not imply practical reversibility at Anthropocene timescales.

Table C4. PETM and hyperthermal phase-level diagnostic matrix. The PETM is treated as a rate- and recovery-sensitivity comparator rather than a canonical BBRS exemplar.

C.3.4 Anthropocene: reflexive closure test under synchronized forcing

Phase	Case expression	Diagnostic evidence / expectation	Constraint, uncertainty, or falsification handle
A. Load emergence	Industrial and land-use systems generate synchronized forcing: CO2, heat, nutrient loading, land transformation, biodiversity pressure, and material throughput.	Great Acceleration synchrony means Phase A is a coupled forcing topology, not one isolated flux.	The relative contribution of each forcing pathway differs by subsystem and timescale.
B. Deceptive Stability Interval	Ocean heat uptake, land/ocean carbon sinks, carbonate chemistry, cryosphere, forests, soils, wetlands, reefs, and institutions buffer the load.	Observed continuity in many metrics can be read as residual stability produced by active buffering.	Some buffers can recover or redistribute, so persistent stability is not automatically depletion.
C. Slack depletion	Increasing observable pass-through, source/sink divergence, regional acidification, incomplete recovery after extremes, reef accretion loss, and institutional lag signal declining margin.	Phase C should appear as pass-through, spatial heterogeneity, incomplete recovery, and buffer-edge deterioration before global means fully shift.	Attribution requires separating true forcing increase from declining absorption efficiency.
D. Threshold proximity / crossing	Subsystem thresholds may be crossed asynchronously: reefs, ice systems, carbon sinks, circulation, forests, and hydrologic buffers need not fail together.	The intervention window closes subsystem by subsystem; aggregate means may lag decisive buffer failure.	The Anthropocene is ongoing, so D and later phases remain partly prospective.
E. Selective	Organisms, infrastructures, insurance systems, supply	Vulnerability should track dependence on baseline	Reflexive action can reduce forcing, restore

vulnerability	chains, emergency institutions, and risk models remain calibrated to buffered normalcy.	conditions made temporarily reliable by active buffering.	buffers, or accelerate closure, so the trajectory is not fixed.
F. Closure or successor regime	Unlike the GOE, dominant byproducts such as CO2 and low-grade heat are largely spent waste; closure requires external non-fossil energy, biospheric uptake, geochemical storage, or technological intervention.	The Anthropocene becomes a reflexive closure test: can the producing system deliberately reclose cycles before buffers stop substituting for closure?	Failure would produce reactive adaptation and constraint tightening rather than automatic energetic succession.

Table C5. Anthropocene phase-level diagnostic matrix. The Anthropocene is an application rather than a completed case because the producing system is reflexive and the intervention window remains partially open.

C.3.5 Ediacaran-Cambrian interval: candidate hypothesis program

Phase	Case expression	Diagnostic evidence / expectation	Constraint, uncertainty, or falsification handle
A. Candidate load	Potential ecological engineering, oxygen/substrate changes, grazing, burrowing, and metabolic/ecosystem innovations alter matground-dominated environments.	A valid BBRS reading requires identifying a persistent load or ecological process that altered the buffering structure before full substrate revolution.	The load-buffer pair remains less defined than GOE or end-Permian.
B. Candidate DSI	Microbial mats and redox microhabitats maintain localized stability despite changing ecological and chemical pressures.	The predicted DSI is microenvironmental: buffered niches and substrate structure persist while their stabilizing capacity weakens.	Evidence may be local, facies-dependent, and difficult to generalize globally.
C. Candidate slack depletion	Weakening matground stabilization, redox structuring, or substrate buffering should appear before the full dominance of bioturbated/ecologically reworked substrates.	Phase C should show ordered transition from matground/redox-buffer stress to ecological release.	If ecological diversification precedes or is unrelated to buffer weakening, BBRS membership weakens.
D. Reorganization	Substrate revolution and ecological expansion reorganize sediment-water interfaces and benthic ecosystems.	A BBRS reading requires that reorganization follows loss of buffering function rather than merely co-occurring with innovation.	Multiple drivers likely interact; BBRS should remain a hypothesis program.
E. Selective vulnerability	Matground-dependent forms and strategies calibrated to buffered microbial substrates lose relative advantage.	Selectivity should track dependence on matground structure, redox microenvironments, and substrate stability.	Poor preservation and ecological novelty complicate selectivity tests.
F. Successor regime	Forms suited to mixed substrates, mobility, burrowing, predation, biomineralization, or oxygenated microhabitats expand.	Phase F candidates should be sought among edge environments where the prior buffering was weakest or less complete.	Absent this ordering, the interval should remain a comparison case rather than a BBRS member.

Table C6. Ediacaran-Cambrian candidate matrix. The matrix is intentionally falsifiable: without evidence of buffer weakening before ecological release, the interval should remain a comparison case.

C.3.6 K-Pg boundary: negative control and mixed press-pulse boundary test

Phase	Case expression	Diagnostic evidence / expectation	Constraint, uncertainty, or falsification handle
A. Forcing	Chicxulub impact imposes acute global forcing; Deccan volcanism complicates the boundary as a possible press component.	The case tests whether severe consequence alone is sufficient for BBRS membership.	It is not a chemically simple single-cause event, so the control must be used narrowly.
B. Pre-threshold interval	No clear BBRS-style Deceptive Stability Interval has to be invoked to explain the main boundary shock.	A positive BBRS reading would require sustained load absorbed by identifiable buffers before the main transition.	If a Deccan-driven press plus slack-depletion sequence is demonstrated, the case becomes mixed rather than cleanly negative.
C. Buffer strain	Any pre-impact environmental stress must be separated from abrupt impact effects.	The relevant test is evidentiary ordering: did declining slack organize the main transition, or did acute forcing dominate?	Boundary complexity should not become a reason to classify all press-pulse events as BBRS.
D. Boundary	A relatively discrete global marker and abrupt ecological	Shock-driven events may leave clear event markers even	Preservation variability still exists, but not

event	consequences dominate the case.	when consequences are severe.	necessarily as process-coupled buffer self-erasure.
E. Selective mortality	Extinction selectivity follows impact-related darkness, food-web collapse, climate perturbation, acidification, and other acute effects.	Selectivity alone is insufficient for BBRS without prior sink-mediated slack history.	If selectivity can be explained without a buffered byproduct load, it supports negative-control status.
F. Recovery	Successor ecosystems reorganize after acute forcing rather than by recruiting a previously accumulated byproduct into a new closure pathway.	The case helps define the boundary: enormous impact does not equal BBRS.	The control remains heuristic because Deccan forcing keeps the boundary from being perfectly clean.

Table C7. K-Pg negative-control matrix. K-Pg is used to test the sufficiency of abrupt consequence, not to claim that the boundary was geologically simple.

C.4 Cross-case discriminator matrix

Diagnostic dimension	Strong BBRS expectation	Best-supported cases	Weak or boundary cases
Observable pass-through	A larger fraction of forcing becomes visible as slack declines; acceleration can reflect weakening absorption rather than source increase alone.	Anthropocene, PETM comparator, GOE	K-Pg; Ediacaran-Cambrian until load/response proxies are clearer
Spatial Phase C geometry	Slack loss appears first at buffer edges, low-capacity regions, or systems bearing redistributed load.	Anthropocene, end-Permian, reefs/carbonate systems	GOE depends on proxy geography; K-Pg is dominated by abrupt shock
Incomplete recovery / cyclic ratchet	Cycles become BBRS-relevant when each recovery fails to restore prior slack or recovery floor.	Anthropocene extremes, PETM/hyperthermal sequences	GOE less obviously cyclic at the relevant scale
Adaptive commitment	Longer or more effective buffering can deepen dependence on the buffered baseline.	Anthropocene institutions/ecosystems, GOE redox ecology, end-Permian specialists	PETM selectivity may be weaker; Ediacaran remains candidate
Archival attenuation	Proxy degradation or missingness should track inferred buffer stress rather than appear randomly.	End-Permian carbonate/redox records, carbonate-buffer cases, Anthropocene archives	K-Pg shock markers may be more discrete; GOE requires careful redox-proxy mapping
Byproduct valence / closure debt	Phase F differs depending on whether the byproduct becomes usable infrastructure or remains spent waste requiring closure.	GOE versus Anthropocene/PETM/end-Permian contrast	Ediacaran uncertain; K-Pg outside core byproduct logic
Falsification handle	A case weakens if it lacks sustained sink-mediated lag, ordered slack depletion, selective dependence, or closure/outcome logic.	All cases	Ediacaran and K-Pg are intentionally boundary-testing cases

Table C8. Cross-case discriminators and falsification handles. The appendix is strongest when used as an exclusion tool as well as a mapping tool.

C.5 Summary

Appendix C’s purpose is to place the framework’s hardest claims in a form that can be challenged. Strong BBRS cases should show ordered sink-mediated lag, declining slack or incomplete recovery, rising observable pass-through or spatial divergence, selective vulnerability tied to buffered-baseline dependence, and a successor-regime outcome constrained by byproduct valence and closure debt.

The key comparison is whether the A-F phase sequence helps explain why the GOE, end-Permian, PETM, Anthropocene, Ediacaran-Cambrian candidate interval, and K-Pg boundary differ in kind. The GOE demonstrates buffered exergy accumulation and energetic succession; the Anthropocene is a reflexive closure test involving spent byproducts; PETM-style hyperthermals show recovery timescale and carbonate compensation; the end-Permian tests compound buffer failure and tolerance succession; the Ediacaran-Cambrian interval tests whether BBRS can generate falsifiable predictions for contested intervals; and K-Pg prevents abrupt consequence from being mistaken for BBRS membership.