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Terra Preta de Índio as an Emergent Ecological Attractor: A Theoretical Hypothesis of Path-Dependence and the Limits of Compositional Replication

Commentary

Abstract

Terra Preta de Índio (Amazonian Dark Earth) has resisted reproducible replication despite decades of study. This commentary advances a falsifiable hypothesis: Terra Preta is not a replicable substrate but may be better interpreted as an attractor-like ecological state arising from path-dependent processes over centuries, associated with persistent fertility, resistance to leaching, and biological self-regulation. A survey of the biochar literature as of 2025 is consistent with a distinctive temporal anomaly: short-term gains (years 1–3) attenuate by years 5–7, with long-term trials (10–15+ years) showing soil-texture-dependent divergence and persistent management dependence. In the literature screened as of 2025, no multi-year withdrawal study was found to have documented autonomous convergence toward Terra Preta-like fertility. A qualitative dynamical framework illustrates how attractor dynamics would generate distinct predictions, including resistance, hysteresis, and basin transitions, that discriminate the attractor hypothesis from compositional optimization. The framework is asymmetrically falsifiable: reproducible creation of self-sustaining fertility within decadal timescales through compositional manipulation alone would refute it. This article defines testable criteria under which multistability could be established or rejected; it does not claim demonstrated multistability.

Keywords: Terra Preta; biochar; emergent ecological state; attractor dynamics; path dependence; soil multistability

Synopsis

- Terra Preta de Índio is proposed as an emergent ecological state shaped by path-dependent processes.
- Biochar trials exhibit only transient fertility gains that attenuate by years 5–7.
- A qualitative dynamical framework generates falsifiable predictions of resistance, hysteresis, and assembly dependence.

1. Introduction

1.1 The Empirical Anomaly

Terra Preta de Índio occupies a singular position in soil science: simultaneously well-characterized and not yet reproducibly engineered. These soils, found throughout the Amazon Basin in association with pre-Columbian settlement, exhibit properties that

challenge conventional pedological models: high fertility apparently persists without management across centuries of abandonment, though the mechanisms sustaining this persistence remain incompletely understood. Cation exchange capacity (CEC) exceeds surrounding oxisols by factors of three to ten (Glaser et al., 2001; Lehmann et al., 2003). Microbial biomass and diversity remain elevated despite no differences in contemporary inputs (Kim et al., 2007). Radiocarbon dating places formation at 500–2500 years BP, coinciding with peak regional population density (Neves et al., 2003), with recent archaeological evidence confirming intentional carbon-rich soil creation (Schmidt et al., 2023).

Recognition of charcoal as a ubiquitous Terra Preta component motivated the biochar replication hypothesis: persistent carbon structures provide the mechanism for long-term fertility. Meta-analyses of short-term trials (1–5 years) report yield improvements averaging 10–25%, with greatest effects in low-fertility substrates (Jeffery et al., 2017). However, a distinctive temporal pattern has emerged across longer monitoring horizons. Short-term gains (years 1–3) attenuate by years 5–7. In rare trials extending to 10–15 years, effects become soil-texture-dependent and management-reliant. In long-term German field experiments, compost combined with 31.5 Mg ha⁻¹ biochar increased SOC stocks by +38 Mg ha⁻¹ in loamy soil, remaining stable after 11 years, whereas in sandy soil treated with 40 Mg ha⁻¹ biochar, initial gains of +61 Mg ha⁻¹ declined to +7 Mg ha⁻¹ after nine years (Gross et al., 2024). Global synthesis indicates sustained benefits require long-term annual re-application; single applications decline over time (Yang et al., 2025). Most meta-analyses synthesize predominantly short-duration experiments, and long-term aging effects remain underexamined (Marazza et al., 2022).

It is important to distinguish two claims: that biochar functions as an effective soil amendment (well-supported) and that biochar application can recreate a Terra Preta-like self-sustaining system (not supported by long-term evidence). The temporal divergence, consisting of early promise followed by attenuation, soil-context dependence, and persistent management requirements, constitutes the central empirical anomaly requiring explanation (synthesized in detail in Section 3).

1.2 Interpretation: Compositional Optimization versus Emergent Attractor

This work proposes that the anomaly may arise because Terra Preta is not engineerable through additive inputs but is an emergent ecological state arising through specific historical trajectories. Here, “attractor” carries its formal dynamical systems sense: a region of state space toward which a system evolves under endogenous dynamics and to which it returns following perturbation. “Emergent” denotes system-level properties arising from component interactions that cannot be predicted from compositional analysis alone. Both terms are operationalized through measurable variables and falsifiable predictions.

Compositional optimization assumes linear forcing: imposed inputs drive predictable convergence. Emergent attractor models assume assembly dependence: system properties arise from historical trajectories and self-organizing feedbacks. Under the former, iterative refinement should yield convergence; under the latter, trials should show initial response followed by long-term divergence. The available empirical literature appears more

consistent with the latter pattern, though this consistency does not exclude simpler explanations, which are addressed in Section 4.2. The inference is abductive: the framework is advanced because it may provide higher explanatory power for the observed temporal pattern, not because nonconvergence proves impossibility. Table 1 summarizes the distinction. This article is offered as a theoretical hypothesis paper: its purpose is not to demonstrate attractor dynamics empirically, but to define a falsifiable systems-level interpretation of the Terra Preta anomaly and the empirical tests required to challenge it.

Table 1. *Two claims about biochar and Terra Preta.*

	Biochar as Soil Amendment	Biochar as Terra Preta Replicator
Claim	Biochar improves soil fertility metrics under management	Biochar application recreates a self-sustaining Terra Preta-like system
Evidence	Well-supported by meta-analyses (Jeffery et al., 2017; Yang et al., 2025)	Not supported by long-term unmanaged trials
Temporal pattern	Positive short-term effects; sustained under re-application	Early gains attenuate; management dependence persists
Predicted trajectory	Proportional dose-response; convergence with refinement	Threshold behavior; hysteresis; path dependence
Disputed here?	No	Yes, reframed as structural misalignment

1.3 Hypotheses

The central hypothesis is that Terra Preta is an emergent ecological state, interpreted here as a hypothesized attractor basin in tropical soil state space, arising from path-dependent processes over centuries. Three specific predictions follow:

Hypothesis 1 (Resistance): Attempts to force conventional soils toward Terra Preta composition through biochar will exhibit resistance rather than convergence. Forcing below threshold intensity produces only transient displacement.

Hypothesis 2 (Hysteresis): Degradation and recovery trajectories will be asymmetric. Moderate disturbance will not collapse system function, whereas recreation from degraded soils will not retrace formation pathways.

Hypothesis 3 (Assembly dependence): Order, timing, and duration of input sequences matter independently of final composition. Identical total inputs in different sequences will diverge in long-term properties.

Figure 1: Compositional vs Emergent Attractor Models with Empirical Trajectories

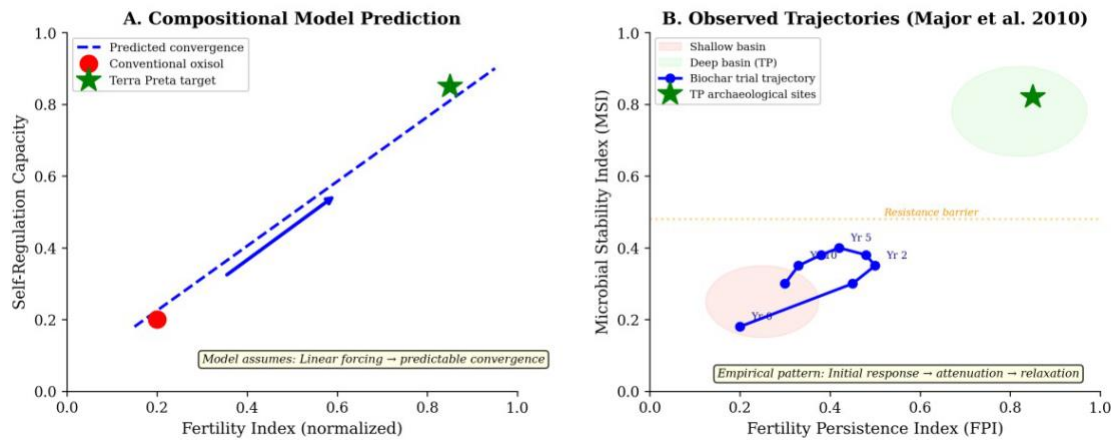


Figure 1. Schematic Illustration of Compositional Forcing versus Attractor-Style Dynamics. Left: linear trajectory predicted under compositional optimization. Right: conceptual state space with two hypothesized attractor basins separated by an activation barrier, showing the expected trajectory of a biochar trial under attractor assumptions. Basin geometry is illustrative, not empirically derived.

Box 1: Established Findings versus Hypothesized Mechanisms.

Element	Status	Evidence Source
Elevated CEC and SOC persistence	Established	Glaser et al., 2001; Lehmann et al., 2003
Distinct microbial community	Established	Kim et al., 2007; Silva et al., 2013
Temporal nonconvergence of biochar trials	Established	Schmidt et al., 2021; Gross et al., 2024
Oligotrophic regulation as stabilizing mechanism	<i>Hypothesis</i>	Inferred from community structure data; falsifiable
Attractor basin classification	<i>Hypothesis</i>	Dynamical model prediction
Asymmetric hysteresis under perturbation	<i>Model prediction</i>	Dynamical model output

2. Methods and Dynamical Framework

2.1 Literature Synthesis and Systematic Search

This study employs a structured narrative synthesis of the biochar and Terra Preta literature, organized by trial duration: short-term (1–3 years), medium-term (5–7 years), and long-term (10–15+ years), compared against archaeological persistence data spanning 500–2000+ years. The synthesis draws on published meta-analyses (Jeffery et al., 2017; Schmidt et al., 2021; Yang et al., 2025), individual long-term experiments (Major et al., 2010; Gross et al., 2024; Jiang et al., 2024), the LTEP-BIOCHAR platform (Marazza et al., 2022), and microbial characterization studies (Kim et al., 2007; Silva et al., 2013). This

manuscript does not present an original statistical meta-analysis; it identifies temporal trajectory patterns across published data. The synthesis is selective by design: it prioritizes studies with sufficient monitoring duration to evaluate trajectory shape. Findings from short-duration experiments and from repeated-application regimes showing sustained benefits are not disputed but are distinguished from the specific question of autonomous, management-independent persistence.

A systematic search of this database, 2024–2025 meta-analyses, and recent field trials identified no explicit multi-year withdrawal study documenting autonomous convergence toward Terra Preta-like fertility in biochar-amended soils, in the sources screened. This empirical gap, the absence of managed-to-unmanaged transition evidence, motivated the falsification criteria proposed in Section 4. This absence is noted as an observational gap in the screened literature, not as evidence against convergence. Withdrawal is rarely the explicit objective of funded biochar trials, and the gap may reflect experimental design priorities and funding constraints rather than system behavior. It is possible that unpublished datasets, industry trials, or ongoing long-term experiments contain relevant withdrawal data not captured by the search strategy employed here.

2.2 Operational Definition

A Terra Preta-like state is defined operationally as a soil system simultaneously satisfying (noting that not all authenticated Terra Preta sites meet every criterion simultaneously; see below): (1) soil organic carbon persistently exceeding 120 g kg^{-1} in the upper 20 cm; (2) effective CEC exceeding 60 cmolc kg^{-1} ; (3) sustained crop productivity without external fertilization for minimum 10 consecutive years, evaluated as yield stability relative to an on-site, same-season control; (4) resistance to nutrient pulse disturbance; and (5) microbial community stability under moderate perturbation. These thresholds are working benchmarks proposed for falsification purposes, not universally necessary criteria for identifying Terra Preta. The values are drawn from the upper range of reported Terra Preta properties (Glaser et al., 2001; Lehmann et al., 2003) and should be treated as provisional benchmarks requiring site-specific calibration. Authenticated Terra Preta sites vary considerably, and some may not meet all five criteria simultaneously; the intent is to set a high bar for claiming replication success, not to define the full empirical distribution. These criteria are intentionally conservative: they are designed to minimize false positives when claiming convergence toward a Terra Preta-like state. ‘Without external fertilization’ means no synthetic fertilizers or imported amendments; in situ biomass recycling is permitted and must be reported. This criterion does not require zero biomass export; sustained productivity is evaluated relative to an on-site control under identical recycling conditions. The distinction between ‘self-sustaining under recycling’ and ‘self-sustaining under harvest removal’ represents a spectrum that future protocols should quantify through defined biomass export thresholds (e.g., minimum grain removal rates).

2.3 Dynamical Model Formulation

Guardrail: This model is not calibrated to Terra Preta and is not presented as a quantitative fit to field trajectories. It is a qualitative structural discriminator, a conceptual tool generating qualitative signatures (threshold behavior, hysteresis, basin-dependent

recovery) that can be tested against compositional optimization expectations. No parameter values are inferred for real Terra Preta sites. The model serves solely to demonstrate that attractor dynamics, if operative, would produce qualitatively different trajectories from those predicted by compositional convergence. It does not constitute evidence that such dynamics are operative.

The model represents soil state as $dS/dt = F(S, B, M)$, where S represents the composite soil state, B stabilized carbon pools, and M microbial and mineral-mediated processes. Terra Preta corresponds to a hypothesized locally stable regime maintained by reinforcing interactions among carbon stabilization, nutrient retention, and microbial structuring. The state variable x represents a normalized composite index combining (with equal weighting) SOC, effective CEC, microbial diversity, and nitrogen retention efficiency, each rescaled to $[0, 1]$. Equal weighting is adopted for simplicity; no empirical or theoretical basis for differential weighting is currently available. Sensitivity of model behavior to alternative weightings has not been assessed and represents a limitation. The forcing term F is a dimensionless scalar representing the net amendment intensity imposed on the system. In the model, basin depth corresponds to the disturbance magnitude required for collapse, and hysteresis width corresponds to the difference between formation and collapse thresholds; neither parameter has been empirically estimated for Terra Preta.

A critical distinction separates century-scale formation from decade-scale stability testing. Formation concerns the historical trajectory through which Terra Preta originally arose, a process spanning centuries that cannot be experimentally reproduced. Stability testing concerns whether the resulting state exhibits attractor properties: resistance to perturbation, hysteresis under forcing, threshold-dependent transitions. Decadal experiments test for attractor-like behavior consistent with hypothesized basin dynamics; they do not claim to recreate formation. In short, the model predicts that experimentally feasible single-application trials will always relax back toward the oxisol basin unless forcing exceeds a critical, multi-decadal threshold.

2.4 Worked Example: Contrasting Compositional and Attractor Predictions

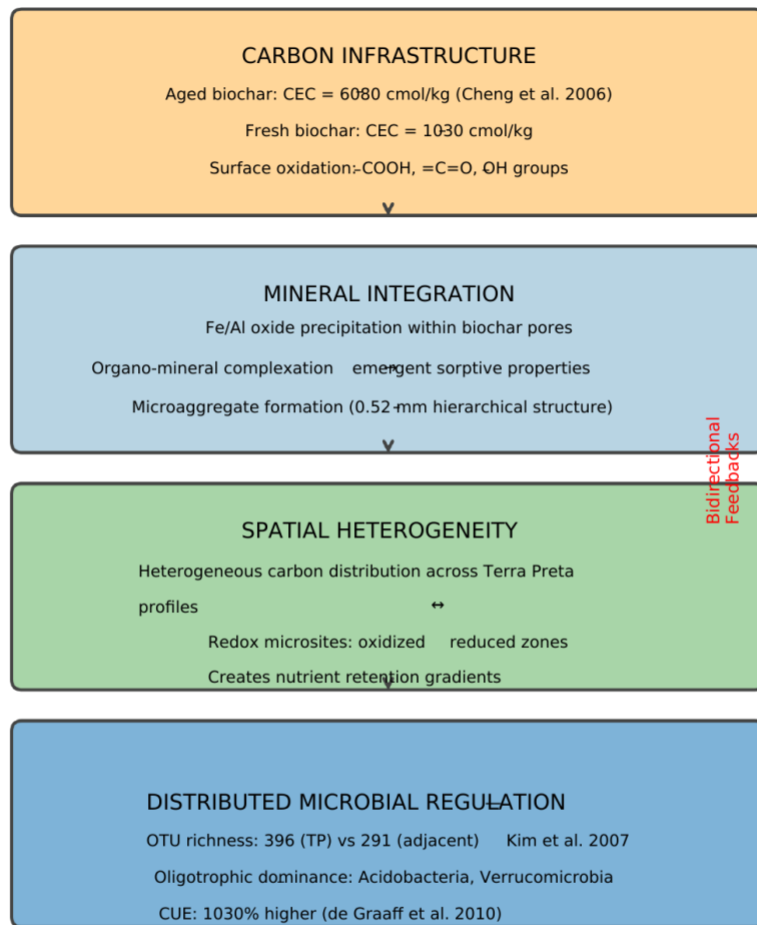
Consider a hypothetical oxisol receiving a single high-rate biochar amendment of 40 Mg ha^{-1} . Under the compositional model, the system should converge toward Terra Preta values given sufficient input. Under the attractor model, the amendment produces a transient displacement: soil properties shift toward intermediate values in the first several years, but if forcing intensity remains below a critical transition threshold, the system relaxes back toward its original state once amendment ceases. This trajectory, initial improvement followed by attenuation, qualitatively parallels the Gross et al. (2024) sandy soil result, where initial SOC gains of $+61 \text{ Mg ha}^{-1}$ declined to $+7 \text{ Mg ha}^{-1}$ over nine years (the model is not calibrated to this dataset and the parallel is illustrative, not quantitative). Under the attractor interpretation, only sustained forcing above threshold intensity, maintained over multi-decadal timescales, could drive transition toward a hypothesized persistent Terra Preta-like state, consistent with the centuries-long archaeological formation record. The compositional model, by contrast, predicts that any sufficient single amendment should produce durable convergence regardless of forcing duration. The key

discriminator is therefore whether gains persist after amendment ceases: the compositional model predicts they should, while the attractor model predicts they will not.

2.5 Empirical Precedent for Soil Bistability

Bistability has not yet been empirically reconstructed for Terra Preta through formal state-space mapping. No published chronosequence has demonstrated two measurable stable equilibria separated by a quantified basin boundary. However, bistability and hysteresis have been documented in other soil and ecological systems at multiple organizational levels: alternative stable microbial community configurations exhibit regime shifts under environmental forcing, and peatland systems demonstrate state persistence maintained by coupled carbon–hydrology feedbacks. These precedents establish that emergent soil states are empirically plausible, though they do not confirm that Terra Preta specifically instantiates such dynamics. The Terra Preta attractor hypothesis is framed as a specific, testable instantiation of soil multistability, motivated by the temporal anomaly described above.

Figure 2: Terra Preta System Architecture (Empirical Measurements)



Emergent stability from integrated architecture, not individual components

Figure 2. Terra Preta System Architecture (Conceptual). Integrated components and hypothesized feedback loops: aged biochar with surface oxidation, mineral integration, spatial heterogeneity, and microbial community regulation. Diagram is illustrative, not empirically derived.

3. Synthesis of Temporal Patterns

3.1 Temporal Trajectory Patterns

Short-term trials (1–3 years): Consistently positive effects: 10–25% yield improvements, enhanced nutrient retention, increased microbial biomass (Jeffery et al., 2017). Effects robust across soil types, greatest in degraded tropical oxisols.

Medium-term trials (5–7 years): Effects attenuated and context-dependent. Yield improvements persist but diminish. Microbial communities shift to intermediate states. Studies report dependence on continued fertilization (Major et al., 2010; Jiang et al., 2024).

Long-term trials (10–15+ years): Outcomes diverge strongly by soil texture. In temperate field trials, biochar effects diverged markedly between loamy and sandy soils over decadal timescales, with stable SOC increases under compost-amended loam but substantial attenuation in sandy soils (Gross et al., 2024). The stable SOC increase in compost-amended loam after 11 years indicates that sustained co-amendment can produce durable soil carbon gains under favorable textural conditions. This does not constitute autonomous persistence, as continued organic inputs were required, but it demonstrates that not all long-term trajectories attenuate. Nevertheless, none of these sustained-gain trajectories have been shown to persist after complete management withdrawal, which remains one of the most direct empirical tests of management-independent persistence. Separately, global synthesis shows annual re-application sustains benefits, whereas single applications decline (Yang et al., 2025). Long-term field datasets remain sparse relative to short-duration experiments (Marazza et al., 2022).

Archaeological contrast: Sites appear to maintain elevated fertility across 500–2000+ years without management (Glaser et al., 2001), though the degree to which low-level disturbance or intermittent use may have contributed to maintenance at some sites is difficult to rule out entirely. SOC stocks approximately three times adjacent soils; black carbon up to 70-fold greater; available phosphorus up to seven times background. Mean black carbon residence times estimated at approximately 556 years for the recalcitrant pool (Wang et al., 2016). Silva et al. (2013) documented distinct microbial community signatures persisting across sites of different ages, a pattern more consistent with biological self-regulation than with compositional inertia alone, though both mechanisms may contribute.

Figure 3: Temporal Divergence — Biochar Trials vs Terra Preta Stability

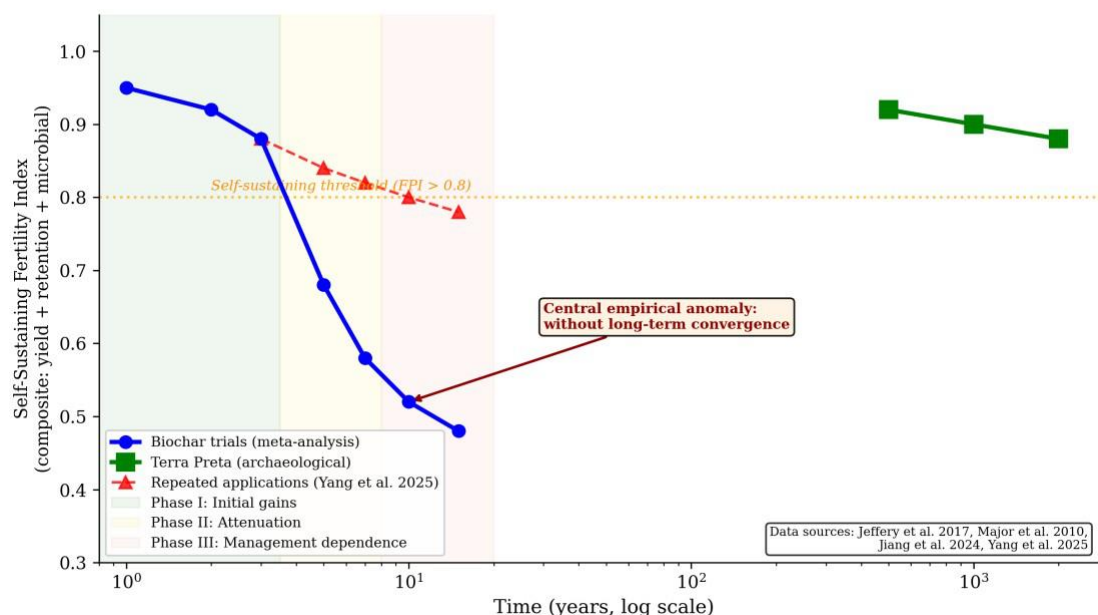


Figure 3. Conceptual Synthesis of Long-Term Biochar Trajectories. Temporal divergence between biochar trial trajectory and archaeological Terra Preta stability across log-scaled time axis. Schematic; not a statistical meta-analysis.

3.2 Pyrogenic Carbon as Physical and Chemical Infrastructure

Some biochar replication narratives implicitly treat carbon as sufficient cause. The emergent framework reinterprets it as necessary infrastructure: pyrogenic carbon and aged biochar surfaces provide habitat for microbial colonization, adsorption sites for nutrient and organic molecule retention, porosity and moisture buffering capacity, microenvironmental heterogeneity across redox and pH gradients, and interfacial surfaces for nutrient retention and biochemical processing. These properties are well documented but do not themselves generate Terra Preta function. Fresh biochar shows CEC of 10–30 cmolc kg⁻¹; oxidized black carbon in aged Terra Preta exhibits 60–80 cmolc kg⁻¹ (Cheng et al., 2006). This difference reflects developmental history: weathering progressively creates oxygen-containing functional groups. In situ aging appears to involve mineral encrustation, microbial biofilm formation, and microaggregate binding, processes that may not be readily imposed through external amendment alone, though this inference rests primarily on observational comparison rather than controlled experimentation. The infrastructure argument is that pyrogenic carbon creates the physical and chemical preconditions within which coupled biological and mineral processes may develop over time, not that carbon addition alone is sufficient to produce an autonomous Terra Preta-like state.

Heterogeneous carbon distribution within Terra Preta profiles creates spatially variable conditions that may support functionally diverse microbial communities. This spatial heterogeneity is absent from uniformly incorporated biochar systems. The framework yields an empirical prediction: soils amended under deliberately heterogeneous regimes should diverge in long-term dynamics from uniformly amended systems, even when total

inputs are equivalent. This prediction has not yet been tested but could be evaluated in the near term through deliberate patch-versus-uniform incorporation trials comparing spatially heterogeneous and homogeneous biochar application at equivalent total rates.

Figure 4: Operationalized Attractor Dynamics Simulation (Illustrative)

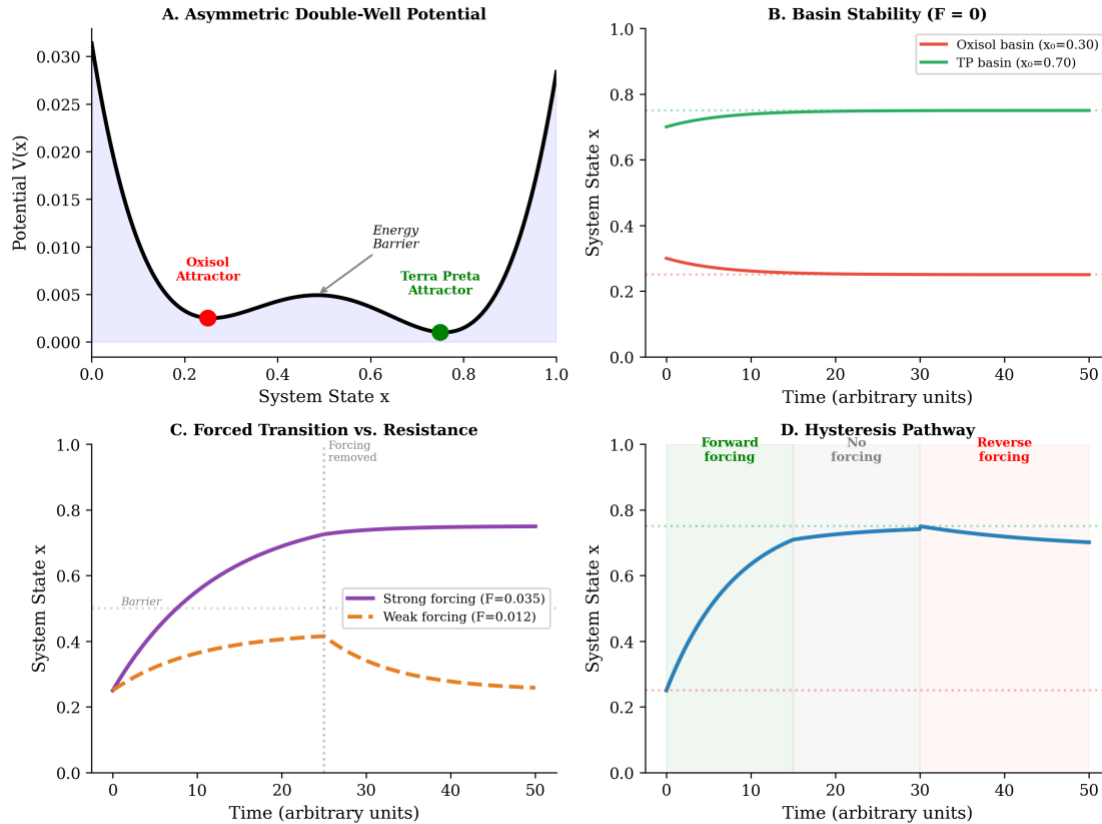


Figure 4. Illustrative Attractor-Style Dynamics. A: Schematic asymmetric double-well potential. B: Conceptual basin stability. C: Strong vs. weak forced transition (illustrative). D: Hysteresis pathway (illustrative). All parameter values and basin geometries are schematic, not empirically derived.

3.3 Microbial Community Structure and the Question of Biological Regulation

Distinct microbial communities have been reported in Dark Earth systems relative to adjacent soils. Kim et al. (2007) documented elevated microbial biomass (two- to five-fold), higher OTU richness (396 versus 291 in adjacent soils), elevated Acidobacteria and Verrucomicrobia, and reduced Proteobacteria dominance in Terra Preta. Silva et al. (2013) found persistent microbial community signatures across Terra Preta sites of different ages. These observations establish that Terra Preta harbors distinctive microbial assemblages, but the causal role of those communities in maintaining long-term fertility remains unresolved.

Available evidence supports a more limited claim: pyrogenic carbon and aged biochar surfaces can provide habitat, adsorption sites, and microenvironmental heterogeneity that

influence colonization, nutrient transformations, and microbial carbon processing over long periods. Biochar-amended soils show higher carbon use efficiency (10–30% increase; de Graaff et al., 2010) and negative priming effects where labile carbon addition slows native organic matter decomposition. Long-term field studies further indicate that biochar can produce persistent shifts in microbial structure and enzyme activity, although these effects are strongly soil-dependent and do not by themselves establish Terra Preta-like autonomous persistence.

Several mechanistic possibilities have been proposed in the literature. Shifts toward slower-growing microbial taxa may reduce rapid nutrient drawdown and increase functional redundancy. Complex trophic networks may create buffering through multiple feedback loops. Spatial heterogeneity within pyrogenic carbon may enable compartmentalized nutrient cycling. These mechanisms are consistent with observed community data but none has been causally demonstrated for Terra Preta. The causal direction remains unresolved: distinctive microbial community structure may be a consequence of altered soil chemistry and physical structure in Terra Preta rather than a driver of its persistence. Determining whether any particular community architecture acts as a stabilizing mechanism, rather than simply reflecting the stable environment, requires manipulation experiments that selectively alter microbial community composition while holding soil chemistry constant.

Microbial regulation therefore remains a plausible component of the attractor interpretation, but its causal role, directionality, and necessary form are empirically open questions. The framework treats biological regulation as a hypothesis to be tested, not an established mechanism.

4. Discussion

4.1 Empirical Predictions and Protocols

Prediction 1 (Resistance): High-rate biochar amendments should show transient displacement without attractor transition. Protocol: paired plots with Terra Preta-equivalent amendments versus unfertilized Terra Preta controls, minimum 15 years, minimum 4 replicate plots per treatment.

Prediction 2 (Hysteresis): Degradation–recovery trajectories should be asymmetric. Protocol: graduated disturbance (0–75% biomass removal, 5 years) followed by 10-year recovery monitoring on authenticated Terra Preta, minimum 3 replicates per disturbance level.

Prediction 3 (Assembly dependence): Temporal sequence should affect outcomes independently of composition. Protocol: factorial designs with staggered, reversed, and simultaneous amendment schedules, 10 years, minimum 3 independent site replications.

4.2 Alternative Explanations

Several competing explanations for the temporal attenuation pattern must be considered before inferring attractor dynamics, and the available evidence does not decisively favor one interpretation over others.

Insufficient cumulative input. Archaeological Terra Preta received centuries of diverse organic additions at unknown rates, while modern trials apply single or few amendments over years to decades. The total carbon and nutrient loading of archaeological sites may simply exceed what any feasible modern experiment can deliver. If the gap is purely quantitative (more material over more time) then attractor dynamics would be unnecessary; slow kinetics and cumulative accumulation would suffice. However, if the issue were simply insufficient total input, one would expect monotonic dose–response relationships. Instead, long-term data show texture-dependent divergence (stable SOC in compost-amended loam, attenuation in sandy soil under equivalent or greater carbon loading) and persistent management dependence rather than gradual convergence. This pattern is more consistent with system-level thresholds than with slow linear accumulation, though cumulative-input effects and threshold effects are not mutually exclusive.

Incomplete carbon aging and slow kinetics. Biochar surface chemistry evolves over decades through oxidation, mineral encrustation, and microbial colonization. Trials spanning 10–15 years may capture only the early phase of a century-scale maturation process. The CEC differences between fresh biochar ($10\text{--}30\text{ cmolc kg}^{-1}$) and aged Terra Preta carbon ($60\text{--}80\text{ cmolc kg}^{-1}$) could reflect time-dependent surface evolution rather than emergent dynamics. This explanation is difficult to distinguish from the attractor hypothesis without explicitly designed aging studies that track functional property development over multi-decadal timescales.

Wrong amendment chemistry, mineral context, or hydrology. Most modern biochar is produced from single feedstocks under controlled pyrolysis, whereas archaeological inputs included heterogeneous mixtures of bone, shell, ash, food waste, and charred vegetation deposited over long periods. Mineral interactions, clay mineralogy, and hydrological regime may all modulate biochar aging and function. Trials conducted in temperate soils with different mineralogy and rainfall patterns than Amazonian oxisols face inherent comparability limitations.

Climatic and pedological mismatch. The majority of long-term biochar trials have been conducted in temperate systems, whereas Terra Preta formed under tropical conditions with distinct weathering regimes, soil fauna, decomposition rates, and mineral cycling pathways. Extrapolating from temperate field data to conclusions about tropical soil dynamics introduces systematic uncertainty. The attenuation pattern observed in temperate trials may partly reflect environment-specific processes rather than general system behavior.

Ordinary management dependence. Most productive agricultural soils require ongoing management inputs. The observation that biochar-amended soils require continued management to sustain gains may simply reflect normal agronomic behavior rather than a

failed attractor transition. Under this view, expecting management-independent persistence from any amendment is an unreasonably high bar derived from the exceptional archaeological case rather than from standard soil science expectations.

Each of these explanations is plausible individually. Some may operate in combination. The cumulative-input confound in particular cannot be resolved by short- or medium-term trials; only multi-decadal withdrawal experiments on soils that have already received equivalent total carbon and nutrient loading to archaeological Terra Preta can discriminate between insufficient forcing and true basin separation. The attractor interpretation is advanced not because these competing explanations have been eliminated, but because it organizes the observed anomaly (the specific pattern of initial response, attenuation, texture-dependent divergence, and persistent management dependence) into a coherent set of testable system-level predictions. If future evidence favors simpler explanations, the attractor framework would be accordingly weakened or refuted.

4.3 Falsification Criteria

The framework would be refuted by: (1) reproducible conversion of conventional soils to stable self-sustaining fertility within 10–20 years through compositional manipulation alone, including via engineered microbial consortia; (2) evidence that authentic Terra Preta rapidly degrades (>50% loss within 10 years) under moderate disturbance without recovery; or (3) identification of treatments that reliably bypass historical contingency across soil types. A fourth line of evidence would materially weaken, though not necessarily refute, the framework: documentation of self-sustaining persistence in systems whose microbial community structure does not differ from that of adjacent non-Terra Preta soils. Such evidence would specifically undermine the hypothesis that distinctive biological regulation is a necessary component of the attractor state, though the broader attractor interpretation could still hold on the basis of carbon, mineral, and physical soil structure alone.

4.4 Synthetic Biology and Engineered Consortia

Advances in synthetic biology raise the question of whether designed microbial communities could bypass centuries of succession. The attractor framework does not dismiss engineered approaches a priori but generates a specific prediction: engineered consortia will not sustain Terra Preta-like properties once external control is relaxed unless embedded within equivalent long-term feedback structures. Current evidence suggests three structural challenges: lack of spatial organization created by heterogeneous carbon infrastructure, competitive displacement by resident communities, and the absence of community architecture that typically arises through sequential succession over extended periods. If future approaches achieve persistent self-regulation following management withdrawal, the emergent state hypothesis would be substantially weakened. This constitutes one of the most tractable near-term tests of the framework.

4.5 Comparative Anthropogenic Soils

The attractor framework may extend beyond Amazonia. European plaggen soils exhibit persistent fertility shaped by centuries of sod-based manuring. African Dark Earths show

similar microbial community shifts and persistent fertility in long-term settlement profiles (Camenzind et al., 2018). Asian paddy soils develop distinctive redox-driven biogeochemistry under millennia of flooded cultivation. Whether these systems represent true alternative attractors or persistent amendment effects remains empirically open, and extension would require independent verification through the same falsification criteria proposed for Terra Preta. The possibility that these systems are simply long-maintained managed soils rather than self-sustaining attractor states cannot be excluded without withdrawal evidence.

4.6 Implications for Soil Management

Biochar demonstrably functions as an effective soil amendment, particularly in degraded tropical soils (Jeffery et al., 2017). These findings are not disputed here. The distinction is between documented biochar utility and formation of a Terra Preta-like state exhibiting self-sustaining fertility without management. A dual-track approach is warranted: continue using biochar as a proven amendment while implementing emergence-oriented practices on experimental plots. Emergence-oriented principles include heterogeneous rather than uniform amendment application, low-intensity continuous inputs (2–5 Mg ha⁻¹ annually rather than single large applications), minimal disturbance regimes, and monitoring trajectory indicators such as microbial community composition trends, shifts in functional group ratios, and decreasing management dependence, rather than static compositional targets. These recommendations are provisional and should be evaluated against long-term experimental evidence as it becomes available.

The framework has direct implications for carbon-removal policy: biochar-based sequestration claims should be evaluated against evidence of autonomous long-term stability rather than short-term carbon addition alone.

4.7 Conservation Priority

If the attractor interpretation is correct, existing Terra Preta sites have irreplaceable value as instances of a state not yet reproducibly engineered. Legal protection, standardized non-destructive research access, Indigenous community stewardship, and economic valuation reflecting potential non-substitutability are warranted. Even under alternative interpretations, these sites represent unique long-term soil–culture systems whose scientific and cultural value justifies precautionary conservation.

4.8 Limitations and Research Agenda

Several critical limitations frame this work as a hypothesis-generating contribution rather than a confirmed theoretical framework. Direct testing is constrained by centuries-long formation timescales. The framework relies on indirect evidence, pattern comparison, and qualitative modeling rather than direct experimental demonstration. The dynamical model is a qualitative structural discriminator, not a calibrated tool; future work should focus on parameter estimation using long-term field data and chronosequences. Once suitable chronosequence datasets with sufficient temporal resolution become available, the qualitative framework presented here could potentially be upgraded to a minimal

calibrated bifurcation model capable of generating quantitative predictions for specific soil–climate combinations.

Five empirical gaps define the priority research agenda. First, no formal state-space mapping has demonstrated bistability in Terra Preta; controlled perturbation–recovery experiments on authenticated sites are needed. Second, no multi-year withdrawal experiment has tested whether biochar-amended soils can maintain enhanced fertility after complete input cessation. Third, the hypothesized role of microbial community structure as a stabilizing mechanism requires direct causal testing through manipulation experiments, not merely correlative community profiling. Fourth, extension of the attractor framework to non-Amazonian anthropogenic soils requires independent demonstrations of multistable dynamics. Fifth, long-term monitoring of engineered microbial consortia following management withdrawal would provide one of the most informative near-term tests of the framework.

Advances in synthetic biology and soil network modeling represent the most plausible near-term challenges to the emergent state interpretation. The model itself should be developed toward spatially explicit representations capturing microbial–carbon coevolution and multi-variable coupled systems incorporating mineral and hydrological feedbacks.

3D Attractor Basin Topology (N_r slice at 0.55)

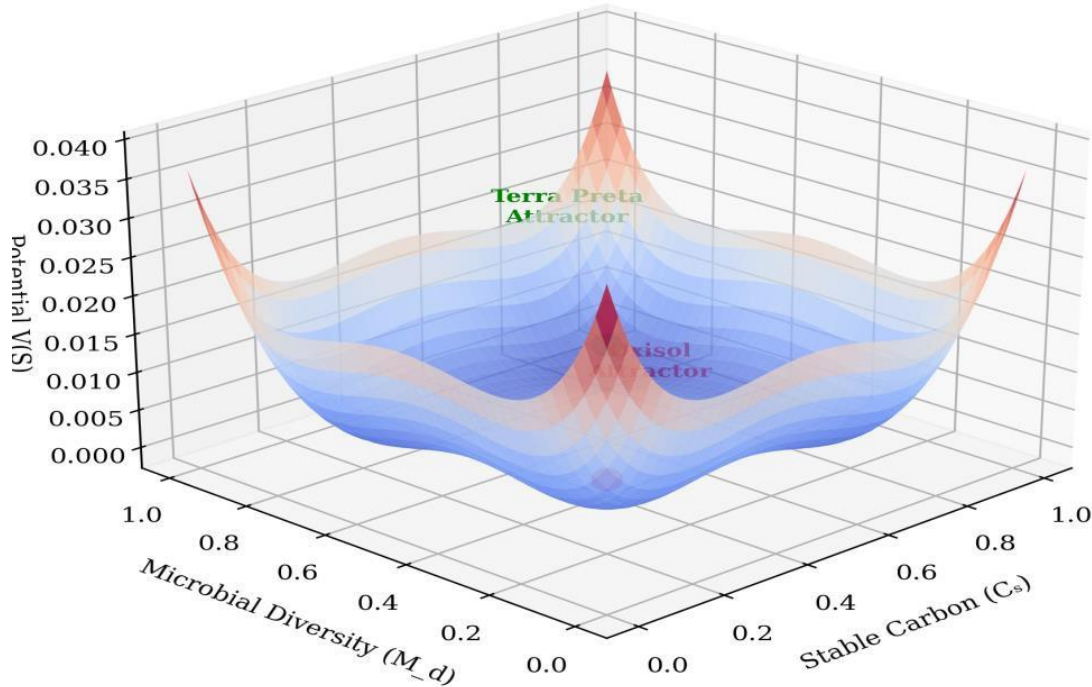


Figure 5. Hypothesized Attractor-Basin Representation. Schematic surface plot of potential $V(S)$ over the C_s - M_d plane at fixed $N_r = 0.55$, showing conceptual oxisol and Terra Preta basins. Basin topology is illustrative and has not been empirically reconstructed.

5. Conclusions

This commentary proposes that Terra Preta may be more accurately understood as an emergent ecological state occupying a hypothesized attractor basin in tropical soil state space, arising from centuries of path-dependent processes. A qualitative dynamical framework illustrates that the attractor hypothesis would generate distinct predictions, including threshold behavior, hysteresis, and asymmetric recovery, that are structurally distinguishable from compositional convergence expectations. Weak forcing, representing experimentally feasible biochar amendments, produces only transient displacement, consistent with the empirical pattern of initial promise without long-term convergence.

This framework does not claim demonstrated multistability in Terra Preta systems. It defines testable structural criteria under which such multistability could be empirically established or rejected. Short-term agronomic enhancement via biochar remains well-supported and operationally valuable. Replication failures are reinterpreted not as evidence of insufficient optimization, but as potentially indicating that compositional logic may be structurally misaligned with a phenomenon governed by path-dependent, historically contingent processes. If the attractor interpretation withstands empirical

testing, the scientific task reframes from recipe optimization to attractor identification: characterizing feedbacks, protecting existing systems, and orienting soil stewardship toward emergence-aligned management.

Box 2: *Glossary of Dynamical Systems Terms.*

Term	Definition
Attractor	A state toward which a dynamical system evolves from nearby initial conditions. Operationally: the soil configuration to which the system returns after perturbation.
Basin of attraction	The set of initial conditions from which a system evolves toward a given attractor. Operationally: the range of soil states from which recovery occurs without external forcing.
Hysteresis	Path-dependent asymmetry: the trajectory from state A to B differs from the reverse. Operationally: degradation and restoration of Terra Preta follow different pathways requiring different forcing magnitudes.
Multistability	Coexistence of two or more stable states under identical external conditions. Operationally: the same climate and parent material can support either oxisol or Terra Preta.
Path dependence	Sensitivity of system state to historical input sequence, not merely cumulative magnitude. Operationally: identical total inputs in different sequences produce different outcomes.
Basin depth	Integrated resistance from equilibrium to basin boundary; a measure of attractor stability. Operationally: the magnitude of disturbance required to induce irreversible state collapse.

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Appendix B: Detailed Experimental Protocols

Protocol 1 (Resistance): Minimum 3 authenticated Terra Preta sites with adjacent controls. Factorial biochar rate (0, 10, 20, 40 Mg ha⁻¹) × organic amendment × mineral enrichment. Duration: 15 years minimum. Minimum 4 replicate plots per treatment (see Section 4.2 for the rationale distinguishing insufficient forcing from true basin separation).

Protocol 2 (Hysteresis): Minimum 2 authenticated sites. Graduated disturbance (0–75% annual biomass removal, 5 years) followed by 10-year recovery. Minimum 3 replicates per disturbance level.

Protocol 3 (Assembly dependence): Amendment order (carbon-first, mineral-first, simultaneous) × temporal spacing (pulse, monthly, continuous). Duration: 10 years. Minimum 3 independent site replications.

Protocol 4 (Microbial regulation): Terra Preta under contrasting nutrient-management regimes expected to favor different microbial community structures (e.g., high-NPK fertilization versus low-input maintenance). Monitor community composition and soil function following management withdrawal at year 5. Duration: 15 years. Minimum 3 sites.

Protocol 5 (Engineered consortia): Biochar-amended soil receiving designed microbial consortia versus controls, management withdrawal at year 5. Duration: 15 years post-withdrawal. Minimum 3 soil types.