Version 2: Revised manuscript with clarified operational definitions, strengthened falsification criteria, and structural refinement.

Terra Preta de Índio as an Emergent Ecological State: Reclassifying a Path-Dependent Attractor from Constructible Substrate

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Reclassifying a Path-Dependent Attractor from Constructible Substrate

Perspective Article

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Abstract

Terra Preta de Índio (Amazonian Dark Earth) has resisted reproducible replication despite decades of study. This perspective advances a falsifiable hypothesis: Terra Preta is not a replicable substrate but an emergent ecological state arising from path-dependent processes over centuries. It appears to occupy a deep attractor basin characterized by persistent fertility, resistance to leaching, and biological self-regulation. A survey of the biochar literature through 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 through 2025, no multi-year withdrawal study was found to have documented autonomous convergence toward Terra Preta-like fertility. An operationalized dynamical model generates distinct predictions—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

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 persists without management across centuries of abandonment. 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—early promise followed by attenuation, soil-context dependence, and persistent management requirements—constitutes the central empirical anomaly requiring explanation.

1.2 Interpretation: Compositional Optimization versus Emergent Attractor

This work proposes that the anomaly arises 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 empirical literature is more consistent with the latter. The inference is abductive: the framework is advanced because it provides higher explanatory power for the observed temporal pattern, not because nonconvergence proves impossibility. Table 1 summarizes the distinction.

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—a deep 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.

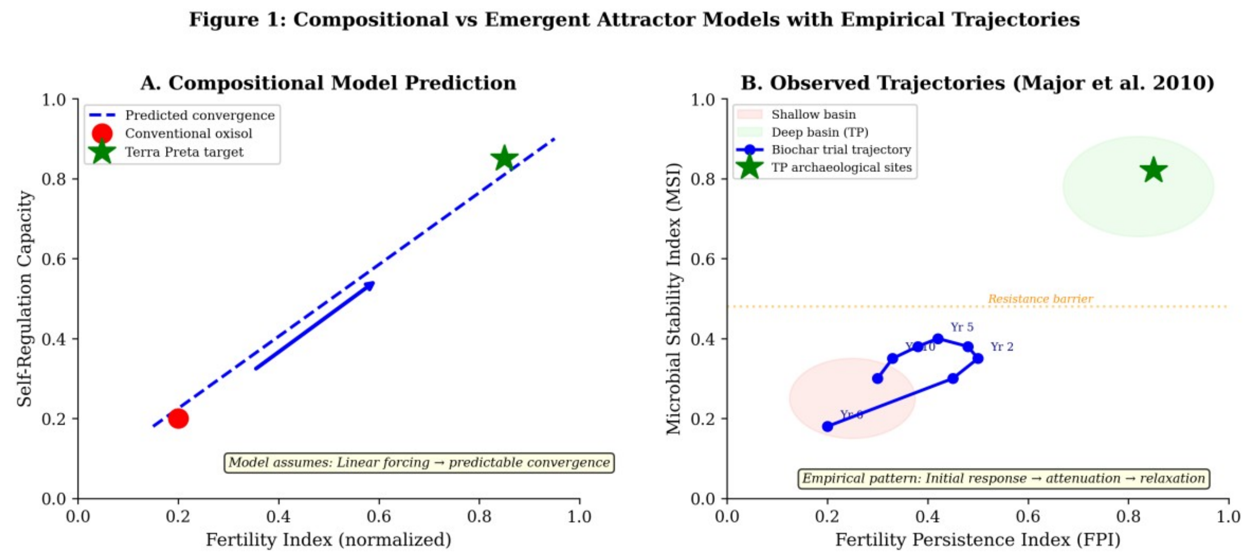

Figure 1. Compositional Forcing versus Emergent Attractor Dynamics. Left: linear trajectory predicted under compositional optimization. Right: state space with two attractor basins separated by activation barrier, showing empirical biochar trial trajectory.

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	*Hypothesis*	Inferred from community structure data; falsifiable
Attractor basin classification	*Hypothesis*	Dynamical model prediction
Asymmetric hysteresis under perturbation	*Model prediction*	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.

A systematic search of the LTEP-BIOCHAR 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.

2.2 Operational Definition

A Terra Preta–like state is defined operationally as a soil system simultaneously satisfying: (1) soil organic carbon persistently exceeding 120 g kg^{-1} in the upper 20 cm; (2) effective CEC exceeding 60 $cmol_t$ 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 are working cut-offs for falsification, not universally necessary thresholds. 'Without external fertilization' means no synthetic fertilizers or imported amendments; in situ biomass recycling is permitted and must be reported.

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 structural discriminator generating qualitative signatures—threshold behavior, hysteresis, basin-dependent recovery—testable against compositional optimization expectations. Specifically, no parameter values are inferred for real Terra Preta sites; the model serves solely to demonstrate that attractor dynamics produce qualitatively different trajectories from those predicted by compositional convergence.

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 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]. The forcing term F is a dimensionless scalar representing the net amendment intensity imposed on the system. Basin depth corresponds to disturbance magnitude required for collapse; hysteresis width corresponds to the difference between formation and collapse thresholds.

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 attractor behavior within existing basins; they do not claim to recreate formation.

2.4 Worked Example: Anchoring the Model to Realistic Ranges

Consider a hypothetical oxisol (SOC ≈ 15 g kg^{-1}, CEC ≈ 8 $cmol_t$ kg^{-1}, Shannon diversity 2.5) receiving a single high-rate biochar amendment of 40 Mg ha^{-1}. Under the compositional model, the system should converge toward Terra Preta values (SOC > 120 g kg^{-1}, CEC > 60 $cmol_t$ kg^{-1}, Shannon > 4.0). In the dynamical model, the initial forcing moves the system state from x ≈ 0.2 toward the activation barrier at x ≈ 0.5. SOC may rise to approximately 40–60 g kg^{-1} within 3 years and CEC to approximately 15–25 $cmol_t$ kg^{-1} (values illustrative, not site-calibrated). However, if forcing intensity (F = 0.012 in dimensionless model units; all numeric parameter values in this example are illustrative and not empirically mapped) falls below the transition threshold (F_crit ≈ 0.03), the system relaxes back once amendment ceases—qualitatively paralleling the Gross et al. (2024) sandy soil trajectory where initial SOC gains of +61 Mg ha^{-1} declined to +7 Mg ha^{-1} over nine years (the model is not calibrated to this dataset). The model predicts that only sustained, multi-decadal forcing above threshold could drive transition into the deep Terra Preta basin at x ≈ 0.8, consistent with the centuries-long archaeological formation record.

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 soil 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 justify treating emergent soil states as empirically grounded possibilities. The Terra Preta attractor hypothesis is framed as a specific, testable instantiation of soil multistability.

Figure 2: Terra Preta System Architecture (Empirical Measurements)

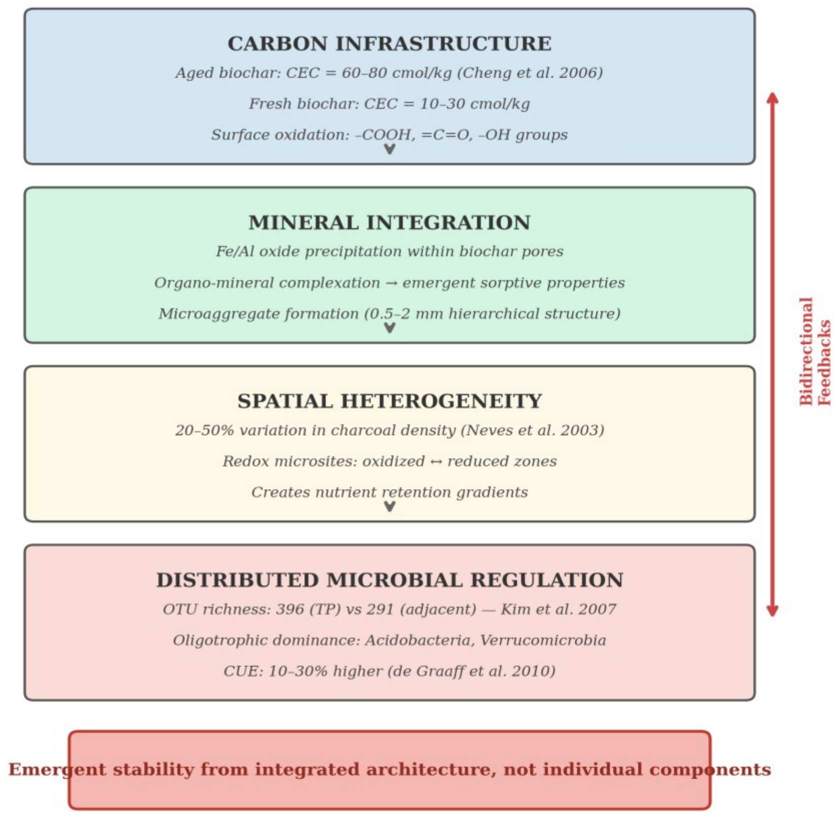

Figure 2. Terra Preta System Architecture. Integrated components and feedback loops: aged biochar with surface oxidation, mineral integration, spatial heterogeneity, and oligotrophic microbial regulation.

3. Evidence Synthesis

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). 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 maintain elevated fertility across 500–2000+ years without management (Glaser et al., 2001). 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, consistent with biological self-regulation rather than compositional inertia.

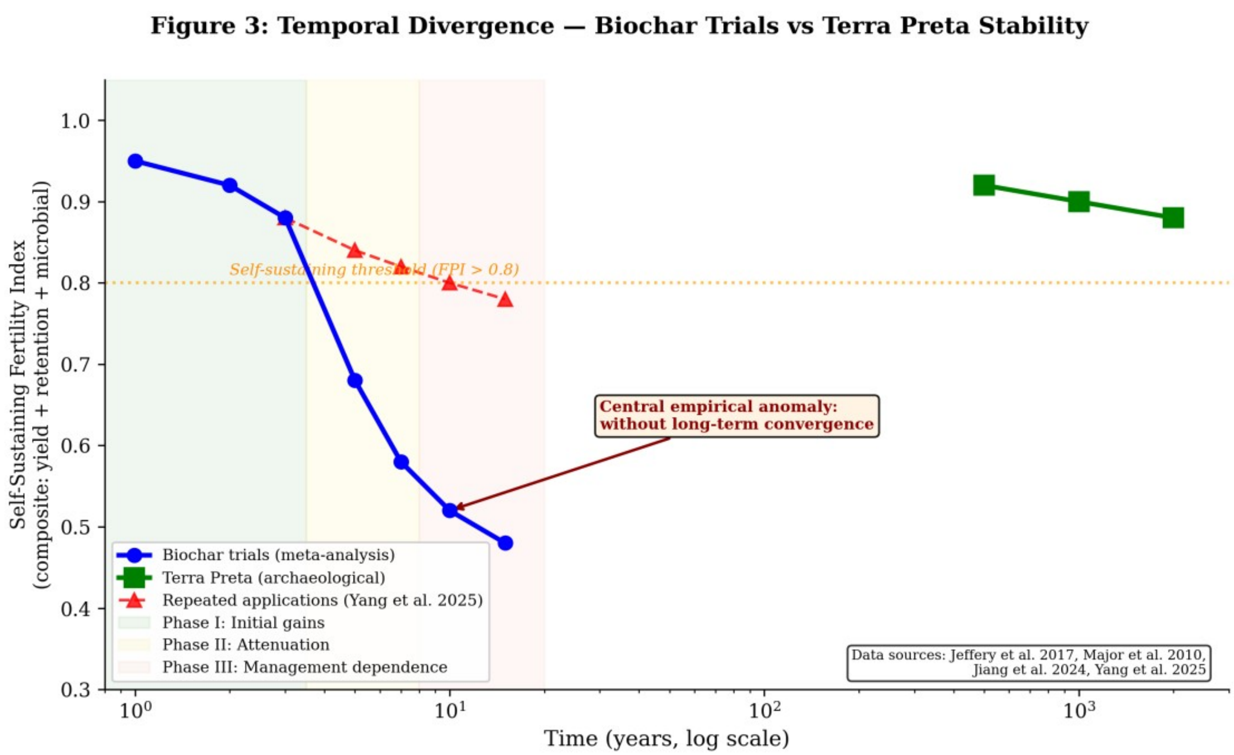

Figure 3. Conceptual Synthesis of Long-Term Biochar Trajectories. Temporal divergence between biochar trial trajectory and archaeological Terra Preta stability across log-scaled time axis. Schematic; not a statistical meta-analysis.

3.2 Carbon as Infrastructure, Not Cause

Many biochar replication narratives implicitly treat carbon as sufficient cause. The emergent framework reclassifies it as necessary infrastructure. Charcoal provides physical scaffolding: surface area for microbial attachment, porosity for water retention, charged sites for cation exchange. These properties are necessary but do not themselves generate Terra Preta function. Fresh biochar shows CEC of 10–30 $cmol_c\ kg^{-1}$; oxidized black carbon in aged Terra Preta exhibits 60–80 $cmol_c\ kg^{-1}$ (Cheng et al., 2006). This difference reflects developmental history: weathering progressively creates oxygen-containing functional groups. In situ aging involves mineral encrustation, microbial biofilm formation, and microaggregate binding—organo-mineral-microbial coevolution that cannot be imposed externally.

The functional significance of heterogeneous carbon distribution—20–50% variation in charcoal density (Neves et al., 2003)—creates redox microsites supporting diverse microbial guilds. 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.

Figure 4: Operationalized Attractor Dynamics Simulation (Illustrative)

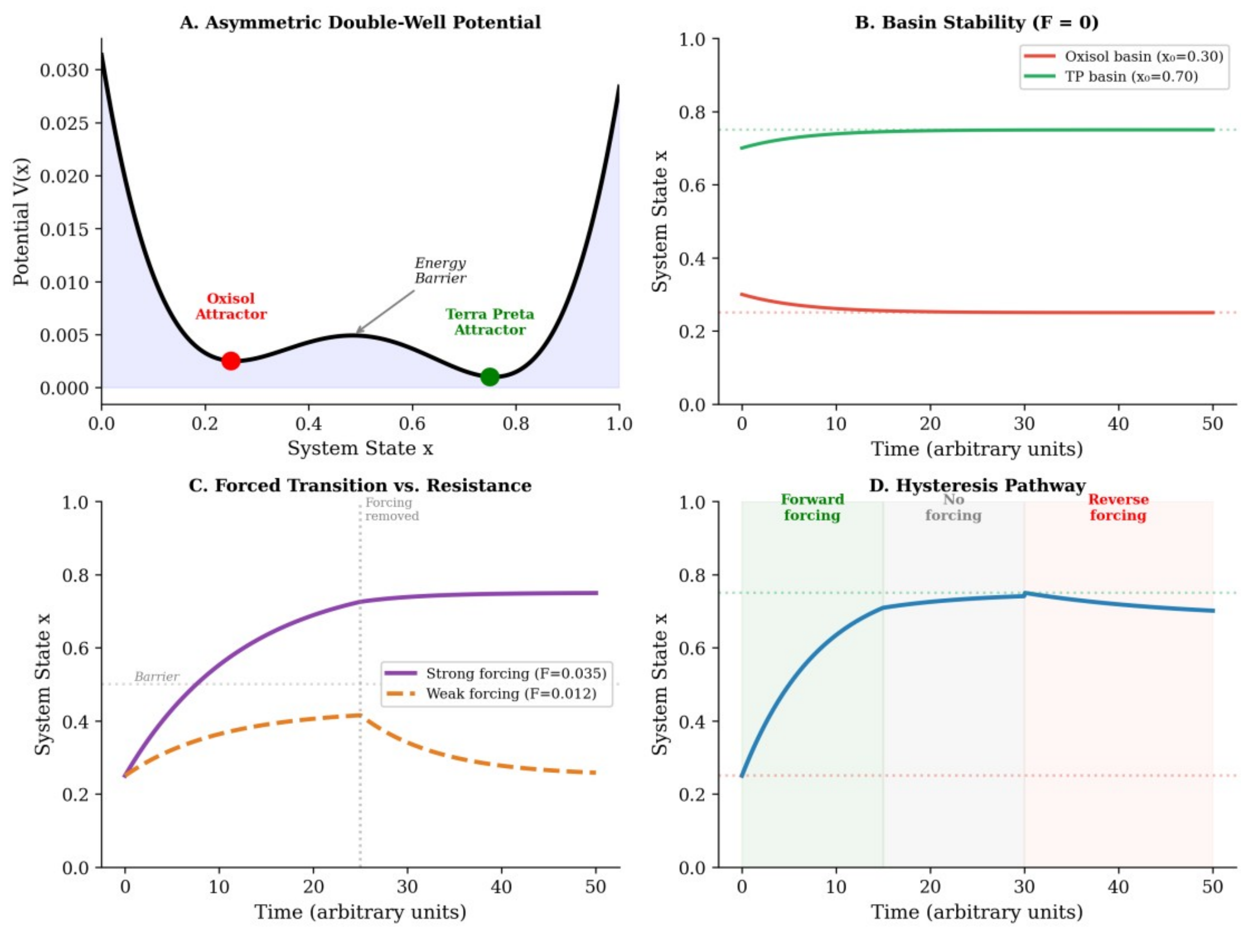

Figure 4. Operationalized Attractor Dynamics Simulation (illustrative). A: Asymmetric double-well potential. B: Basin stability. C: Strong vs. weak forced transition. D: Hysteresis pathway. Parameter values are illustrative.

3.3 Biological Regulation as a Coupled State Variable

Terra Preta supports two- to five-fold elevated microbial biomass relative to adjacent soils (Kim et al., 2007). More significant than quantity is community structure: Terra Preta microbiomes show dominance by slow-growing oligotrophic taxa, high functional redundancy, and network architectures characteristic of mature systems. Kim et al. (2007) documented OTU richness of 396 versus 291 in adjacent soils, with elevated Acidobacteria and Verrucomicrobia, reduced Proteobacteria dominance, 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.

Inferential links (labelled as such): Three mechanistic pathways are hypothesized to connect microbial structure to attractor stability. First, oligotrophic dominance may prevent rapid nutrient drawdown and provide functional redundancy against perturbation. Second, complex trophic networks may create buffering through multiple feedback loops. Third, spatial heterogeneity may enable compartmentalized cycling where nutrient pulses are processed through compartments with distinct retention times. These pathways are consistent with, but not proven by, available microbial community data. Oligotrophic dominance as a predicted necessary condition for persistence requires direct empirical validation. If persistence were documented in systems lacking oligotrophic dominance, the biological regulation claim would be substantially weakened.

4. Predictions, Falsification, and Implications

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 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; (3) identification of treatments that reliably bypass historical contingency across soil types; or (4) documentation of persistence in systems lacking oligotrophic microbial dominance.

4.3 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 requirement for oligotrophic network architecture that arises through sequential succession over decades to centuries. If future approaches achieve persistent self-regulation following management withdrawal, the emergent state hypothesis would be substantially weakened.

4.4 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.

4.5 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 attractor exhibiting self-sustaining fertility without management. A dual-track approach is warranted: continue using biochar as a proven amendment while implementing emergence-aligned practices on experimental plots. Emergence-aligned 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—microbial diversity trends, oligotrophic-to-copiotrophic ratio shifts, decreasing management dependence—rather than static compositional targets.

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.

4.6 Conservation Priority

If Terra Preta represents an attractor state not yet reproducibly engineered, existing sites have irreplaceable value. Legal protection, standardized non-destructive research access, Indigenous community stewardship, and economic valuation reflecting non-substitutability are warranted.

5. Limitations and Research Agenda

Several critical limitations frame this work as a hypothesis-generating contribution rather than a confirmed reclassification. Direct testing is constrained by centuries-long formation timescales. The framework relies on indirect evidence, modeling, and comparative studies. 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.

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 oligotrophic microbial networks as stabilizing mechanisms requires direct causal testing, not merely correlative community profiling. Fourth, the comparative indices (FPI, CSR, MSI) proposed here remain heuristic tools requiring independent validation against field data (see Appendix A for formulae). Fifth, extension of the attractor framework to non-Amazonian anthropogenic soils requires independent demonstrations of multistable dynamics.

Advances in synthetic biology and soil network modeling represent the most plausible challenges to the emergent state interpretation. Long-term monitoring of engineered consortia following management withdrawal would provide critical tests. The model itself should be developed toward spatially explicit agent-based representations capturing microbial–carbon coevolution and multi-variable coupled systems incorporating mineral and hydrological feedbacks.

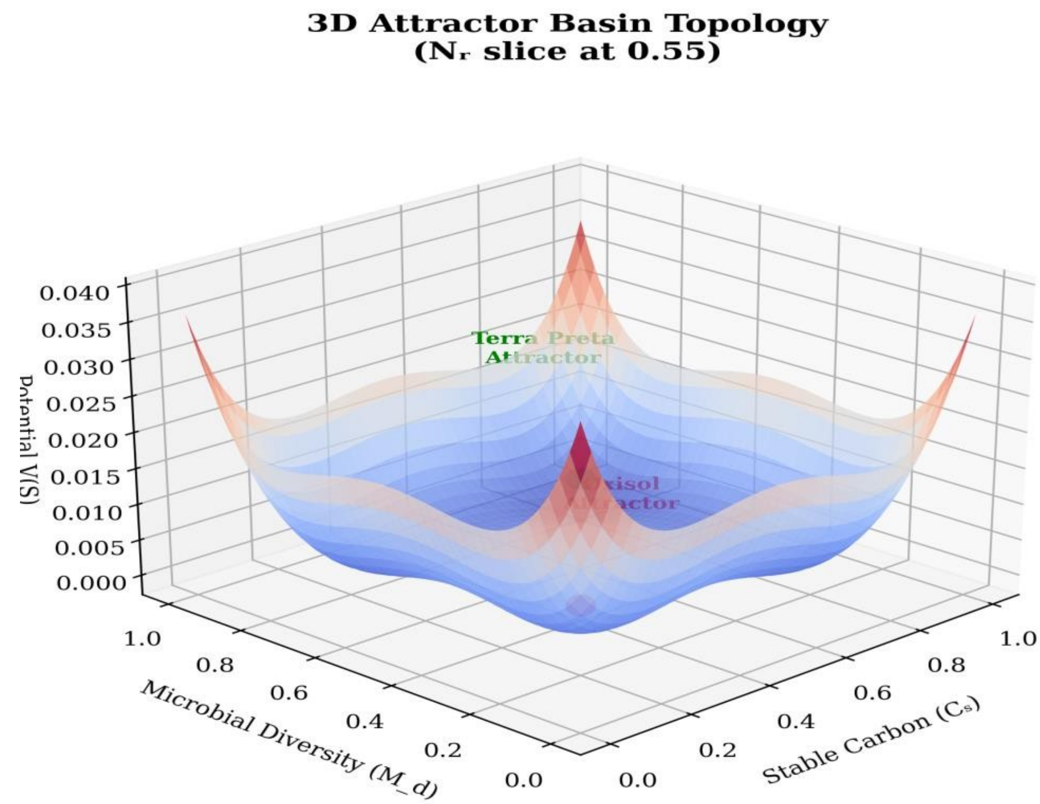

Figure 5. Three-Dimensional Attractor Basin Topology. Surface plot of potential V(S) over the C_s–M_d plane at fixed N_r = 0.55, showing oxisol and Terra Preta basins.

6. Conclusions

This perspective reclassifies Terra Preta as an emergent ecological state occupying a deep attractor basin in tropical soil state space, arising from centuries of path-dependent processes. An operationalized dynamical model demonstrates that the attractor hypothesis generates quantitatively distinct predictions regarding resistance, hysteresis, and basin transitions. 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 as evidence that compositional logic may be structurally misaligned with a phenomenon governed by complex adaptive systems dynamics. The scientific task reframes from recipe optimization to attractor identification: characterizing feedbacks, protecting existing systems, and orienting soil stewardship toward emergence alignment.

Box 2: Glossary of Dynamical Systems Terms

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.

Declarations

Competing Interests: The author declares no known competing financial interests or personal relationships that could have influenced this work.

Ethical Compliance: This study involved no human participants, animal subjects, or field interventions requiring ethical approval.

Author Contributions: Stuart Lance Wilkins: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review and editing, Visualization.

Data Availability: No primary data were generated. All referenced data are from published sources. Simulation parameters are described in Section 2.3 and Appendices.

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Appendix A: Comparative Index Formulae

Three derived conceptual indices structure cross-study comparison. These are heuristic tools for pattern identification, not validated metrics. No inferential claims are made from index values alone.

Fertility Persistence Index (FPI): FPI = (Yield_no_input / Yield_initial_peak) × (Nr_current / Nr_initial). Requires a defined yield metric, a stated initial peak window, and a nitrogen-retention proxy.

Carbon Stability Ratio (CSR): CSR = (Stable Carbon Fraction after t years) / (Initial Carbon Addition). Requires initial added carbon quantity and post-t measurement of pyrogenic carbon. If only total SOC is available, CSR must not be computed.

Microbial Stability Index (MSI): MSI = (Shannon diversity × Functional redundancy) / Disturbance sensitivity coefficient. Requires a diversity metric, a functional proxy, and a defined disturbance protocol. If any component is missing, report qualitatively only. Proxy examples:

“Functional redundancy” may be operationalized via metagenomic pathway richness (e.g., number of KEGG ortholog groups per functional category). “Disturbance sensitivity coefficient” may be operationalized via the proportional change in Shannon diversity following a standardized nutrient-pulse perturbation (e.g., 50 kg N ha^{-1} addition, measured at 30 and 90 days post-application).

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.

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 (Oligotrophic regulation): Terra Preta under oligotrophic maintenance versus copiotrophic forcing (high-NPK). Monitor persistence following withdrawal at year 5. Duration: 15 years. Minimum 3 sites.

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