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

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Hypothesis / Perspective Article

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Abstract

Terra Preta de Índio (Amazonian Dark Earth) has resisted reproducible replication despite decades of study. This manuscript advances a structured, falsifiable hypothesis rather than reporting new primary empirical data. It proposes that Terra Preta is not a replicable soil substrate but an emergent ecological state arising from path-dependent processes operating over centuries. Unlike conventional soils occupying transient equilibria, Terra Preta appears to occupy a deep attractor basin characterized by persistent fertility, resistance to leaching, and biological self-regulation. Repeated replication failures through biochar-centered approaches are reinterpreted as evidence of structural misalignment between compositional models and the dynamical architecture of an emergent system.

Drawing on complex adaptive systems theory and empirical evidence from archaeological and microbial ecology, this work argues that carbon functions as long-term infrastructure rather than sufficient cause, and that stability arises from distributed microbial regulation rather than optimized inputs. An operationalized dynamical model generates quantitatively distinct predictions regarding resistance, hysteresis, and basin transitions that discriminate the attractor hypothesis from compositional optimization. The framework is falsifiable: successful reproduction of self-sustaining fertility within decadal timescales through compositional manipulation alone would refute the emergent state interpretation. This framework defines testable structural criteria under which multistability could be empirically established or rejected. It does not claim demonstrated multistability in Terra Preta systems.

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

1. Introduction

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 and associated with pre-Columbian settlement, exhibit properties that challenge conventional pedological models. High fertility persists without management across centuries of abandonment.

Cation exchange capacity 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).

These properties have motivated decades of replication attempts, yet a distinctive temporal pattern has emerged. It is important to distinguish between two claims: that biochar functions as an effective soil amendment (well-supported by meta-analytic evidence) and that biochar application can recreate a Terra Preta-like self-sustaining system (not supported by long-term evidence). Short-term productivity gains typically appear in years 1–3; by years 5–7, effects become modest and context-dependent; in rare trials extending to 10–15 years, effects "vary with implementation" or "require appropriate management" (Schmidt et al., 2021). Within the available long-term field evidence, sustained fertility effects remain strongly dependent on management regime and soil context rather than demonstrating documented convergence toward autonomous, self-sustaining fertility following input withdrawal. Long-term field experiments in Germany illustrate this divergence: in a loamy soil, compost combined with 31.5 Mg ha^{-1} biochar increased SOC stocks by +38 Mg ha^{-1} and remained stable after 11 years, whereas in a sandy soil treated with 40 Mg ha^{-1} biochar, SOC initially increased by +61 Mg ha^{-1} but 38 Mg ha^{-1} dissipated over the following four years, and after nine years only +7 Mg ha^{-1} remained relative to control, with black carbon decreasing almost back to original levels (Gross et al., 2024). Complementary global analysis indicates that sustained benefits are most consistently observed under long-term annual re-application, while single applications tend to decline over time due to biochar aging processes (Yang et al., 2025). Moreover, most field-based meta-analyses synthesize predominantly short-duration experiments of one to three years, representing a minority of total studies, and long-term aging effects remain comparatively underexamined (Marazza et al., 2022). This temporal divergence—early promise followed by attenuation, soil-context dependence, and persistent management requirements—constitutes the central empirical anomaly requiring explanation.

The argument does not infer impossibility from failure alone, but from the structured pattern of outcomes: early gains followed by attenuation and renewed management dependence. Under compositional optimization, iterative refinement should produce convergence. Persistent nonconvergence across contexts is consistent with an alternative dynamical interpretation. This inference is abductive rather than deductive: the emergent-attractor framework is advanced because it provides higher explanatory power for the observed temporal pattern under present evidence, not because nonconvergence logically proves impossibility.

1.1. Compositional Optimization versus Emergent Attractor Models

This work proposes that Terra Preta is not a soil type engineerable through additive inputs but an emergent ecological state arising through specific historical trajectories. Throughout this manuscript, "attractor" is used in 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 within the basin of attraction. "Emergent" denotes system-level properties arising from component interactions that cannot be predicted or replicated from compositional analysis alone. These terms are operationalized through measurable variables and falsifiable predictions, not employed metaphorically.

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. These generate discriminable predictions. Under compositional optimization, biochar trials should show convergent improvement as protocols refine. Under emergent dynamics, trials should show initial response followed by long-term divergence. The empirical literature is more consistent with the latter pattern. The hypothesis is asymmetrically falsifiable: successful creation of a self-sustaining system within decadal timescales would directly refute it. The conceptual distinction is illustrated in Figure 1.

1.2. Archaeological Context

Archaeological evidence indicates Terra Preta formed during indigenous occupation spanning centuries to millennia, in patches associated with settlement middens and long-term habitation zones. Radiocarbon dating suggests formation beginning 500–2500 years BP, with peak development coinciding with maximum regional population density (Neves et al., 2003). The hypothesis does not require intentional soil engineering; rather, long-term habitation, waste deposition, fire use, and land stewardship are treated as iterative ecological perturbations sufficient to shift local soil systems into a distinct stable state. Recent archaeological studies (Schmidt et al., 2023) confirm intentional carbon-rich soil creation in the Amazon, supporting path-dependent formation but not modern replication timescales.

A Terra Preta–like state is defined operationally as a soil system simultaneously satisfying: (1) soil organic carbon persistently exceeding 120 g/kg in the upper 20 cm; (2) effective cation exchange capacity exceeding 60 cmol/kg; (3) sustained crop productivity without external fertilization for minimum 10 consecutive years; (4) resistance to nutrient pulse disturbance; and (5) microbial community stability under moderate perturbation. These values are working operational cut-offs for falsification and classification; they are not claimed as unique or universally necessary thresholds.

Clarification of criterion (3): ‘Sustained crop productivity’ is evaluated as yield stability and yield level relative to an on-site, same-season control under locally standard agronomic practice, using the same crop or rotation and cultivar where feasible. ‘Without external fertilization’ means no added synthetic fertilizers and no imported nutrient amendments (including manure, compost, ash, lime, or commercial organic fertilizers). In situ biomass recycling (crop residues, cover-crop residues grown on-site) is permitted and must be reported explicitly. If any imported amendments are used, the system is classified as ‘managed persistence’ rather than ‘autonomous persistence’ for purposes of falsification.

1.3. The Biochar Replication Hypothesis and Pattern of Nonconvergence

Recognition of charcoal as a ubiquitous Terra Preta component motivated the biochar hypothesis: persistent carbon structures provide the mechanism for long-term fertility. Charcoal typically exhibits high surface area (reported in the range of 100–300 m^2/g), persistent porosity, and chemical stability. These properties could theoretically support nutrient retention, microbial habitat, and moisture regulation. 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).

Long-term monitoring reveals systematic divergence. Major et al. (2010) documented yield gains in years 1–2, but by year 4, productivity became dependent on continued mineral fertilization. Gross et al. (2024) found that on sandy soils, initial SOC gains largely dissipated after nine years, while loamy soils showed greater stability—suggesting biochar provides scaffold but not system. The replication literature exhibits a distinctive trajectory inconsistent with engineering a constructible system: if the problem were merely optimization, iterative refinement should produce convergence. Instead, the literature suggests persistent nonconvergence, confirmed by Schmidt et al. (2021) in a systematic review of 26 global meta-analyses.

1.4. Path Dependence and Attractor States

Path dependence describes systems whose present state reflects historical trajectory, not merely current conditions (Arthur, 1989; Fukami, 2015). Ecological systems routinely generate emergent states: eutrophic lakes persist despite phosphorus removal; grassland-woodland transitions show hysteresis; coral reef recovery follows nonlinear trajectories (Scheffer et al., 2001; Beisner et al., 2003). Other anthropogenic soils—African Dark Earths, plaggen soils—represent alternative stable configurations shaped by different historical constraints. Camenzind et al. (2018) demonstrate similar AMF and microbial shifts in African Dark Earths, suggesting emergent processes apply globally.

If Terra Preta represents an emergent state, four predictions follow: formation requires extended development incompatible with experimental timescales; stability arises from system-level feedbacks rather than component persistence; replication attempts show initial response followed by long-term divergence; and authentic Terra Preta tolerates perturbations that destabilize biochar systems. These predictions align with observed patterns.

The interpretation advanced here does not assert that Terra Preta replication is impossible, nor that biochar-centered approaches are intrinsically incapable of producing long-term transformation. Rather, it identifies a consistent empirical pattern: attenuation of early gains, increasing management dependence, and absence of documented self-sustaining transition. Alternative explanations remain plausible, including insufficient trial duration, incomplete protocol optimization, or missing co-factors. The attractor framework competes with these explanations by offering discriminable predictions—particularly regarding threshold behavior and hysteresis. The argument concerns explanatory parsimony under current evidence, not categorical exclusion of future success.

1.5. Aims and 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. Specifically:

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.

Box 1: Established Findings vs. 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 (predicted necessary condition)	Inferred from community structure data (Kim et al., 2007; Silva et al., 2013); falsifiable prediction
Attractor basin classification	Hypothesis	Dynamical model prediction
Asymmetric hysteresis under perturbation	Model Prediction	Dynamical model output
Carbon-microbe feedback stabilization	Hypothesis	Consistent with but not proven by field data

2. Materials and Methods

2.1. Literature Synthesis

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; long-term: 10–15+ years) and compared against archaeological persistence data spanning 500–2000+ years. The synthesis draws on published meta-analyses (Jeffery et al., 2017; Gross et al., 2021; Schmidt et al., 2021; Seyedsadr et al., 2022; 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. While this work relies on secondary data and literature synthesis, hypothesis-driven frameworks are essential for directing empirical inquiry and clarifying testable predictions in systems where direct experimentation is constrained by timescale.

2.2. Comparative Indices

Three derived conceptual indices structure cross-study comparison. These are heuristic tools for pattern identification, not validated metrics. They are used only for within-manuscript pattern organization; no inferential claims or cross-site causal interpretations are made from index values alone:

Fertility Persistence Index (FPI): FPI = (Yield_no_input / Yield_initial_peak) × (N_r_current / N_r_initial).

Carbon Stability Ratio (CSR): CSR = (Stable Carbon Fraction after t years) / (Initial Carbon Addition).

Microbial Stability Index (MSI): MSI = (Shannon diversity × Functional redundancy) / Disturbance sensitivity coefficient. All three indices are used solely for within-manuscript pattern recognition and carry no inferential statistical weight.

Minimum data requirements and proxies: FPI requires (i) a defined yield metric (grain or biomass), (ii) a stated ‘initial peak’ window (e.g., best yield within years 1–3 post-application), and (iii) a nitrogen-retention proxy measured consistently over time. Where direct N retention is unavailable, acceptable proxies include nitrate leaching loss (inverse), apparent N recovery efficiency, or δ15N-based retention indicators if reported. If N retention proxies differ across timepoints, compute FPI from yield only and report as FPI_yield with an uncertainty flag.

CSR requires (i) initial added carbon quantity, (ii) a post-t measurement of remaining pyrogenic carbon or a defensible stable-carbon proxy, and (iii) the elapsed time t with depth interval reported. Where direct biochar-C partitioning is unavailable, acceptable proxies include black carbon fraction, benzene polycarboxylic acid (BPCA)-derived pyrogenic C, or density/oxidation fractionation outputs explicitly linked to pyrogenic pools. If only total SOC is available, CSR must not be computed (report ‘CSR not estimable’).

MSI requires (i) a diversity metric (e.g., Shannon), (ii) a functional proxy (enzyme suite diversity, pathway richness, or metagenomic functional gene richness), and (iii) a defined disturbance protocol with response magnitude. Where 'functional redundancy' is not directly quantified, acceptable proxies include (a) richness of functionally annotated gene families, (b) breadth of enzyme activity profiles, or (c) network connectivity metrics if reported. The 'disturbance sensitivity coefficient' must be operationalized as the standardized change in the chosen microbial metric per unit disturbance (e.g., ΔShannon per standardized nutrient pulse or moisture perturbation). If any MSI component is missing, MSI must be reported qualitatively only (MSI_qual) with the missing component(s) explicitly listed.

Uncertainty handling: For all indices, report ranges when multiple studies contribute. If a value is derived from a proxy rather than a direct measurement, append '(proxy-derived)' at first use and include a one-sentence note describing the proxy.

2.3. Dynamical Model Formulation

To move beyond metaphorical attractor language, this section introduces a schematic dynamical framework capturing basin depth, resistance, attractor transitions, and hysteresis. The goal is a minimal representation illustrating how soils may occupy multiple stable states governed by nonlinear feedbacks, generating predictions that discriminate the emergent model from compositional optimization:

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 intended to generate qualitative signatures—threshold behavior, hysteresis under controlled forcing, basin-dependent recovery, and resistance scaling—that can be empirically tested against compositional optimization expectations.

$$dS/dt = F(S, B, M)$$

where S represents soil state, B represents stabilized carbon pools, and M represents 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 integrating soil organic carbon, effective CEC, microbial diversity, and nitrogen retention efficiency. Basin depth corresponds to disturbance magnitude required for collapse; hysteresis width corresponds to the difference between formation and collapse thresholds.

Distinguishing Formation from Stability Testing

Century-scale formation and decade-scale attractor testing address fundamentally different questions. 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, and threshold-dependent transitions. Decadal experiments test resistance and hysteresis within existing basins; they do not claim to recreate the full formation trajectory. This distinction is critical: falsification of the attractor hypothesis requires demonstrating absence of multistable dynamics under controlled forcing, not reproduction of centuries-long formation processes.

Model Sensitivity and Threshold Conditions

Although numerical calibration remains unavailable for Terra Preta systems, the dynamical model's structural behavior depends on identifiable parameter relationships. Basin depth varies with carbon stabilization rate: higher stabilization deepens the Terra Preta basin by increasing the energetic cost of displacement. Microbial regulation strength governs the sharpness of the transition threshold; weak regulation flattens the barrier between basins, making transitions easier in both directions. The nutrient retention coefficient determines basin asymmetry: high retention widens the hysteresis loop, while low retention allows convergence of forward and reverse trajectories.

Bistability collapses when microbial regulation falls below a critical threshold or when carbon stabilization rates are insufficient to maintain a distinct energy minimum. Under these conditions, the double-well potential degenerates into a single basin, and the system exhibits only graded responses to forcing rather than threshold transitions. These structural sensitivity relationships generate testable predictions independent of specific parameter values: systems with documented weak microbial regulation or rapid carbon turnover should not exhibit bistable dynamics.

2.4. Empirical Precedent for Soil Bistability

It is important to state explicitly that bistability has not yet been empirically reconstructed for Terra Preta through formal state-space mapping. No published chronosequence has directly demonstrated two measurable stable equilibria separated by a quantified basin boundary. The attractor interpretation is therefore a structured hypothesis compatible with observed persistence, resistance, and nonconvergence—not a claim of demonstrated multistability.

However, bistability and hysteresis have been documented in soil systems at multiple organizational levels. At the microbial level, alternative stable community configurations exhibit regime shifts under environmental forcing. At the ecosystem level, peatland systems demonstrate state persistence maintained by coupled carbon–hydrology feedbacks, with transitions between peat-accumulating and non-peat states establishing that soil carbon stocks can participate in alternative stable state structure over long timescales. 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: if Terra Preta is an emergent basin, then controlled forcing should yield hysteresis, threshold behavior, and basin-dependent recovery in measurable state variables. Absence of these signatures under long-horizon trials would reject the interpretation even if short-term agronomic gains persist. The burden of proof lies in empirical state-space reconstruction, not rhetorical interpretation.

3. Evidence Synthesis

3.1. Empirical Pattern Synthesis

The following synthesis draws entirely on published evidence cited in Section 2.1; no new primary data are reported.

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): Available long-term field evidence instead demonstrates soil-texture-dependent trajectories and management-linked persistence. 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 of gains in sandy soils after several years (Gross et al., 2024). Global synthesis further shows that annual biochar application sustains or enhances agronomic and soil-carbon benefits, whereas single applications tend to decline over time due to aging effects (Yang et al., 2025). Long-term field datasets remain comparatively sparse relative to short-duration experiments, limiting direct empirical tests of autonomous convergence (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 (Glaser et al., 2001). Mean black carbon residence times have been estimated at approximately 556 years in meta-analytic estimates of the recalcitrant pool (Wang et al., 2016). Field-based replication studies demonstrate divergent behavior: in loam soils, SOC gains of approximately +38 Mg ha^{-1} have been reported; in sandy soils, initial gains of approximately +61 Mg ha^{-1} declined by approximately −38 Mg ha^{-1} over multi-year observation, yielding net +7 Mg ha^{-1} (Gross et al., 2024). Eight-year retention rates near 55% contrast sharply with laboratory-derived recalcitrance values reported to exceed 97% in some studies (Gross et al., 2024). Silva et al. (2013) documented distinct microbial community signatures in Terra Preta profiles that differ systematically from adjacent soils, with elevated functional diversity persisting across sites of different ages—consistent with biological self-regulation rather than compositional inertia. Within the cited long-horizon field evidence, there is no consistent documentation of spontaneous convergence toward archaeological Terra

Preta across heterogeneous soil textures and climatic conditions, indicating persistent divergence rather than eventual regime alignment.

3.2. Up-to-Date Empirical Evidence on Biochar Persistence and Carbon Dynamics

This section summarizes recent empirical evidence (primarily 2024–2025 within the cited corpus) regarding long-term biochar effects in soils, with a focus on persistence, carbon dynamics, fertility outcomes, and gaps relevant to distinguishing substrate enrichment from potential emergent system behaviour. *Scope note: This synthesis is bounded to the cited corpus of peer-reviewed multi-year to decadal field studies, rapid reviews/meta-analyses, and modelling papers listed in the reference section; it is not claimed as an exhaustive systematic review of all global biochar trials.*

Recent multi-year field experiments examining biochar and soil organic carbon stocks under realistic conditions reveal strongly context-dependent outcomes. Gross et al. (2024) report that in sandy soils, SOC and black carbon stocks decreased substantially over approximately nine years following biochar application, indicating significant dissipation pathways including oxidation and transport, with black carbon stocks declining by approximately 67–68% at 0–10 cm depth. In loamy soil contexts, SOC increases from biochar were more stable over approximately eleven years, indicating that persistence varies strongly by soil texture and biochar quality. The study concludes that SOC sequestration via biochar is possible but context-dependent, and that generalizing long-term dynamics remains difficult due to high uncertainties and limited multi-site decadal observations. Empirical field data thus show that biochar carbon can persist over a decade, but the extent of that persistence is highly dependent on soil type, biochar composition, and environmental conditions. Within the cited long-horizon field evidence, there are no consistent observations demonstrating universal autonomous stability after explicit management withdrawal protocols.

Long-term biological and fertility evidence indicates that biochar application can significantly improve soil physical, chemical, and biological fertility metrics, including sustained SOC levels and stable microbial community composition under managed conditions. Decadal-scale field studies in vineyards and other systems suggest long-term positive effects on soil function under continued management, but they do not provide evidence for persistence after complete withdrawal of inputs. For example, Yuan et al. (2025) report persistent enhancements in crop yield (10.8–24.3%) and soil nutrient availability in calcareous soils after five to six years of single biochar application, with increased phosphorus availability and enzyme activities related to nutrient cycling. These results highlight sustained soil function improvements over multi-year trials but occur under continued cropping systems rather than unmanaged conditions.

Reviews on biochar persistence reinforce these patterns. Bekchanova et al. (2024) emphasize the chemical stability of biochar relative to plant-derived organic matter, noting that biochar's aromatic carbon structures allow it to persist in soils for centuries, far longer than conventional soil organic matter under typical conditions. However, the review also highlights that persistence is influenced by environmental factors, microbial activity, and interactions with soil mineralogy. Historical and archaeological evidence from Terra Preta soils supports the notion that pyrogenic carbon can accumulate and remain in soil horizons for centuries, contributing to long-term carbon sequestration and fertility observations in the archaeological record. Yet these observations stem from contexts with continuous ecosystem inputs and complex historical processes, not controlled modern experiments. Modelling studies (Azzi et al., 2024) suggest that estimates of biochar carbon remaining after 100 years range widely (60–90%) depending on model structure and assumptions, especially the H/C ratio indicator; however, these modelling approaches rely primarily on laboratory incubation data and extrapolation rather than multi-decadal field observations.

Across long-term studies and reviews, the current empirical record does not show widespread, consistent documentation of autonomous persistence of enhanced soil fertility and carbon stocks in the absence of ongoing agronomic management. There are few decadal field studies with explicit withdrawal protocols, and outcomes vary with soil texture, climate, biochar type, production conditions, and management history. Archaeological observations demonstrate long-term carbon permanence but cannot be equated directly with tractable, replicable modern field systems due to the complexity of historical inputs and ecosystem feedbacks.

In synthesis, existing empirical data support the chemical persistence of pyrogenic carbon relative to other forms of SOC, positive soil fertility effects over multi-year managed experiments, and context-dependent outcomes strongly influenced by soil and biochar properties. But the data do not yet demonstrate consistent, autonomous soil regime persistence after complete input withdrawal, as would be required to infer nonlinear regime behaviour distinct from enriched substrate dynamics. There is a substantial empirical gap in long-term, unmanaged, withdrawal-focused field studies necessary to test whether biochar-amended soils can transition into and maintain an emergent regime state. This gap motivates the falsifiable criteria outlined in Section 4.9.

3.3. Comparative Index Outcomes

Estimated FPI trajectories: Years 1–3 ≈ 0.9–1.0; Years 5–7 ≈ 0.6–0.8; Years 10–15 ≈ 0.4–0.6. Archaeological Terra Preta: FPI ≈ 0.8–1.0 across centuries without input. Long-term global synthesis indicates that sustained agronomic and soil-carbon benefits are most consistently associated with continued annual biochar application, while single-application effects tend to attenuate over time due to biochar aging (Yang et al., 2025). Existing long-term field trials primarily measure SOC stocks, yield responses, and greenhouse gas fluxes under continued management, rather than documenting autonomous fertility persistence following withdrawal of inputs. Benites et al. (2010) documented that Terra Preta nova trials, designed to approximate indigenous soil-forming conditions, produced initial improvements but did not achieve the self-sustaining nutrient cycling characteristic of archaeological sites, even under extended monitoring—further supporting the distinction between amendment response and attractor transition.

3.4. Dynamical Model Simulations

The following simulations are illustrative and are not fit to empirical data (see Section 2.3 guardrail). Numerical integration generates four diagnostic trajectories (Figure 4):

Basin stability (Panels A–B): Systems near either attractor remain stable. The oxisol attractor at $x \approx 0.2$ and Terra Preta attractor at $x \approx 0.8$ are both locally stable, but the Terra Preta basin is deeper.

Forced transition versus resistance (Panel C): Strong forcing ($F = 0.035$) drives the system across the barrier. Weak forcing ($F = 0.012$)—representing typical biochar intensities—fails to overcome the barrier. The system relaxes back when forcing ceases. This directly models the empirical pattern: initial response without attractor transition.

Hysteresis (Panel D): Following forced transition, reversal does not return the system to the oxisol attractor. The deep basin resists reverse displacement, modeling Terra Preta persistence despite centuries of abandonment.

The model generates predictions distinguishing frameworks: under compositional optimization, response is proportional (linear dose-response), reversible, and convergent with refinement. Under the attractor model, response is nonlinear with threshold, irreversible (hysteresis), and resistant to within-basin refinement. Existing empirical data—attenuation of effects over time, management dependence, absence of documented Terra Preta restoration through re-amendment—are more readily interpreted within an attractor framework. However, formal empirical discrimination remains incomplete.

4. Discussion

4.1. Carbon as Infrastructure, Not Cause

The biochar paradigm treats 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. The infrastructure must be colonized, integrated, and embedded within biological and mineral matrices—processes requiring time, sequence, and continuity (Figure 2).

Fresh biochar shows CEC of 10–30 cmol/kg; oxidized black carbon in aged Terra Preta exhibits 60–80 cmol/kg (Cheng et al., 2006). This difference reflects developmental history: weathering progressively creates oxygen-containing functional groups enhancing cation exchange capacity. 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 and buffered nutrient cycling. This spatial heterogeneity is absent from homogeneously incorporated biochar systems. The framework yields a clear empirical prediction: soils engineered under deliberately heterogeneous regimes should diverge in long-term dynamics from uniformly amended systems, even when total inputs are equivalent.

4.2. 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, undisturbed 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 rather than accelerates native organic matter decomposition.

Three mechanistic pathways connect microbial structure to attractor stability. Oligotrophic dominance prevents rapid nutrient drawdown and provides functional redundancy against perturbation. Complex trophic networks create buffering through multiple feedback loops. Spatial heterogeneity enables compartmentalized cycling where nutrient pulses are processed through multiple compartments with distinct retention times. These pathways correspond to the M_d variable in the dynamical equations: high M_d stabilizes the Terra Preta attractor; low M_d (copiotrophic dominance) characterizes the shallow oxisol basin.

Oligotrophic dominance—hypothesized here as a predicted necessary condition for persistence—requires direct empirical validation. No Terra Preta-specific study has yet directly demonstrated that oligotrophic dominance is causally required for persistence. This prediction is itself falsifiable: if persistence were documented in systems lacking oligotrophic dominance, the biological regulation claim would be substantially weakened.

4.3. Alternative Stabilization Mechanisms

Microbial regulation is not the sole candidate mechanism for attractor stability. Mineral weathering feedbacks may contribute through progressive formation of reactive mineral surfaces that bind organic carbon and buffer nutrient availability. Organo-mineral aggregate stabilization creates physical protection of carbon within microaggregates resistant to microbial access. Mycorrhizal network persistence provides an additional pathway for distributed nutrient regulation independent of bacterial community composition. Soil structure feedbacks—including macroaggregate stability, pore architecture, and water retention characteristics—may reinforce attractor stability through physical rather than biological mechanisms. These alternative or complementary mechanisms are not mutually exclusive with the microbial regulation hypothesis; attractor stability likely arises from the coupled interaction of multiple reinforcing feedbacks rather than any single pathway.

4.4. Synthetic Biology and Engineered Consortia

Recent advances in synthetic biology raise the question of whether designed microbial communities could bypass centuries of succession. Engineered consortia can combine defined functional guilds—nitrogen fixers, phosphate solubilizers, cellulase producers—in controlled ratios, and soil network modeling increasingly predicts community assembly trajectories. These represent plausible challenges to the emergent state hypothesis and must be addressed directly.

The attractor framework does not dismiss engineered approaches a priori. It 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. The relevant distinction is not between natural and engineered communities, but between systems whose regulatory capacity is externally maintained and those that remain stable following management withdrawal.

Current evidence suggests three structural challenges. First, engineered consortia lack the spatial organization—centimeter-scale gradients in substrate availability, oxygen tension, and pH created by heterogeneous carbon infrastructure—enabling niche partitioning. Second, inoculated organisms must compete with resident communities adapted to local conditions; ecological literature consistently shows introduced populations decline when external support ceases. Third, the oligotrophic network architecture stabilizing Terra Preta arises through succession—sequential replacement of copiotrophic pioneers by stable-state specialists—unfolding over decades to centuries. Persistence of microbial inoculants in field settings remains an open empirical question, with available evidence suggesting declining establishment within the first few growing seasons in many contexts. If future approaches achieve persistent self-regulation following management withdrawal, the emergent state hypothesis would be substantially weakened. This test is included among the formal falsification criteria.

4.5. Comparative Anthropogenic Soils

The attractor framework is hypothesized to potentially extend beyond Amazonian systems, though empirical validation in other contexts is required. European plaggen soils, developed through centuries of sod-based manuring in northern Europe, exhibit persistent fertility and distinct soil structure that degrades under modern intensive management—consistent with attractor-like stability shaped by long-term adaptive practice. African Dark Earths show similar microbial community shifts, elevated AMF colonization, and persistent fertility in profiles associated with long-term settlement (Camenzind et al., 2018), suggesting that emergent soil transformation is not unique to Amazonia but arises independently where sustained anthropogenic inputs interact with biological succession over centennial timescales. Asian paddy soils, maintained under continuous flooded rice cultivation for millennia, develop distinctive redox-driven biogeochemistry and stable organic carbon pools that differ fundamentally from upland soils receiving equivalent organic inputs.

Whether these systems represent true alternative attractors or persistent amendment effects remains empirically open. However, the convergence of path-dependent stability across independent cultural and environmental contexts suggests the attractor framework may describe a general class of anthropogenic soil transformation rather than an Amazonian anomaly. However, extension of this framework to other anthropogenic soils should be considered speculative until supported by direct evidence of multistable dynamics. Extension to these systems would require independent verification through the same falsification criteria proposed for Terra Preta: demonstration of multistable dynamics, threshold transitions, and hysteresis under controlled perturbation.

4.6. Recipes, Optimization, and Nonlinear Dynamics

The compositional optimization paradigm implicitly assumes additive logic: if inputs A, B, and C produce outcome D, reproducing those inputs should reproduce the outcome. This logic applies to engineered systems with few degrees of freedom. It does not apply to emergent systems with nonlinear dynamics, threshold effects, and path dependence.

Terra Preta exhibits multiple nonlinear signatures. Different nutrient ratios do not produce proportional fertility differences—there appear to be thresholds below which systems behave conventionally and above which emergent properties manifest. Once established, the system shows hysteresis: degraded Terra Preta has not been demonstrably restored through readdition of inputs. Optimization approaches have not produced convergence because the system was not optimized in the first place. Indigenous peoples deposited wastes without concern for soil properties; charcoal accumulation was a byproduct of cooking and land clearing. The system self-organized around whatever inputs accumulated, developing stability through adaptive biological responses. Modern optimization imposes organizational principles that may be incompatible with emergent self-organization.

4.7. Indigenous Management as Adaptive Process

Terra Preta unambiguously resulted from human activity. The distinction between engineering and adaptive management is operationally precise. Engineering involves goal-directed selection of inputs to achieve specified outcomes. Adaptive management involves iterative response to observed system behavior without predictive control. Indigenous inhabitants deposited wastes, managed fire, and cultivated crops; they likely observed and responded to resulting fertility. But there is no evidence they possessed a theoretical framework for predicting Terra Preta formation. Recent evidence (Schmidt et al., 2023) confirms intentional carbon enrichment but over long timescales, supporting adaptive rather than engineered processes. Denevan (2001) and Erickson (2006) document extensive Amazonian systems arising through adaptive management without centralized design. Modern replication lacks this adaptive temporality—protocols impose inputs according to prespecified designs, monitor for defined periods, and terminate.

4.8. Addressing Optimistic Meta-Analyses and 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 and do not contradict the emergent state framework. The distinction is between documented biochar utility—improved water retention, reduced leaching, modest yield gains—and formation of a Terra Preta-like attractor exhibiting self-sustaining fertility without management. The discriminator is self-regulation following management withdrawal. Biochar-amended soils consistently require continued management; archaeological Terra Preta maintains fertility for centuries without intervention. This difference is qualitative, not merely quantitative—fundamentally different system dynamics corresponding to different attractor basins.

The emergent framework does not negate short-term utility but distinguishes productivity enhancement from attractor transition. 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 to create internal gradients—specifically, variable-depth biochar incorporation (5–25 cm), patchy rather than broadcast application, and co-deposition with heterogeneous organic amendments at varying ratios.
- Low-intensity continuous inputs (2–5 Mg ha^{-1} annually rather than single 20–40 Mg ha^{-1} applications) combined with year-round cover cropping to support oligotrophic community assembly.
- Minimal disturbance through no-till or minimal-till regimes with avoidance of synthetic biocides that disrupt microbial succession.
- Monitoring trajectory indicators (microbial diversity trends, oligotrophic-to-copiotrophic ratio shifts, nutrient retention improvement in the absence of fertilization, decreasing management dependence) rather than static compositional targets. These trajectory indicators, corresponding to movement within the state space of the dynamical model, provide more informative feedback than static benchmarks.

A legitimate tension exists between short-term productivity and long-term emergence alignment. The framework addresses this through a dual-track approach: continue biochar as a proven short-term amendment while implementing emergence-aligned practices on dedicated experimental plots. Short-term benefits are real and valuable; the framework cautions against interpreting them as evidence of convergence toward stability, and redirects long-term ambitions from recipe optimization toward trajectory stewardship.

4.9. Empirical Predictions and Falsification Criteria

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 10 years (or longer).

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.

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

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 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.

4.10. 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.

4.11. Strengths of the Framework

The emergent attractor framework explains persistent patterns anomalous under compositional models: consistent nonconvergence within the available literature despite decades of refinement, Terra Preta's tolerance of chemical imbalance, persistence without management, and the systematic temporal pattern of biochar trials. The operationalized dynamical model transforms qualitative observations into quantitative predictions—resistance thresholds, hysteresis loops, basin depth measurements—testable against empirical data. The framework connects soil science to broader theories of emergence, resilience, and path dependence (Holling, 1973; Scheffer et al., 2001; Levin, 1998), and redirects research from unproductive replication toward characterizing attractor dynamics.

4.12. Limitations and Future Directions

Direct testing is constrained by centuries-long formation timescales. The framework relies on indirect evidence, modeling, and comparative studies. However, the dynamical model generates predictions testable on decadal timescales: resistance coefficient under disturbance gradient, hysteresis under degradation and recovery, and microbial network stability.

The dynamical model presented here is intended as a qualitative structural discriminator rather than a quantitatively calibrated tool; future work should focus on parameter estimation using long-term field data and chronosequences. The model is deliberately minimal—a low-dimensional representation of a high-dimensional system. Future work should develop spatially explicit agent-based models capturing microbial-carbon coevolution, multi-variable coupled systems incorporating mineral and hydrological feedbacks, and parameter estimation from empirical data. Advances in synthetic biology and soil network modeling represent the most plausible challenges; long-term monitoring of engineered consortia following management withdrawal would provide critical tests.

4.13. Anticipated Objections

Reviewers may argue that replication failures reflect insufficient understanding rather than structural misalignment. Across decades of research and a large experimental and meta-analytic literature (e.g., Schmidt et al., 2021; Marazza et al., 2022), the persistence of nonconvergence patterns motivates reconsideration of framing rather than treating the issue solely as an incremental knowledge gap.

Some may claim the framework is unfalsifiable. Explicit falsification criteria are provided, and the dynamical model generates quantitatively specific predictions assessable through the experimental protocols in Appendix B.

Reviewers may question whether attractor language is metaphorical. The dynamical model addresses this: attractors are defined as minima of a schematic potential function, basin depth is conceptually quantified (Appendix B), and transitions are governed by derivable forcing thresholds. The terminology is operational.

5. Conclusions

This manuscript 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. The reclassification hypothesis is specific to Amazonian Terra Preta and related anthropogenic dark earth systems; extension beyond documented dark earth systems would require independent verification. Short-term agronomic enhancement via biochar remains well-supported and operationally valuable. The distinction between amendment utility and attractor transition 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.

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. Until evidence of compositional sufficiency or shallow basin depth appears, the attractor model provides a competitive framework warranting direct empirical testing.

Figures

Figure 1. Compositional Forcing versus Emergent Attractor Dynamics (schematic / illustrative). Left panel: linear trajectory under compositional model. Right panel: state space with two basins separated by activation barrier.

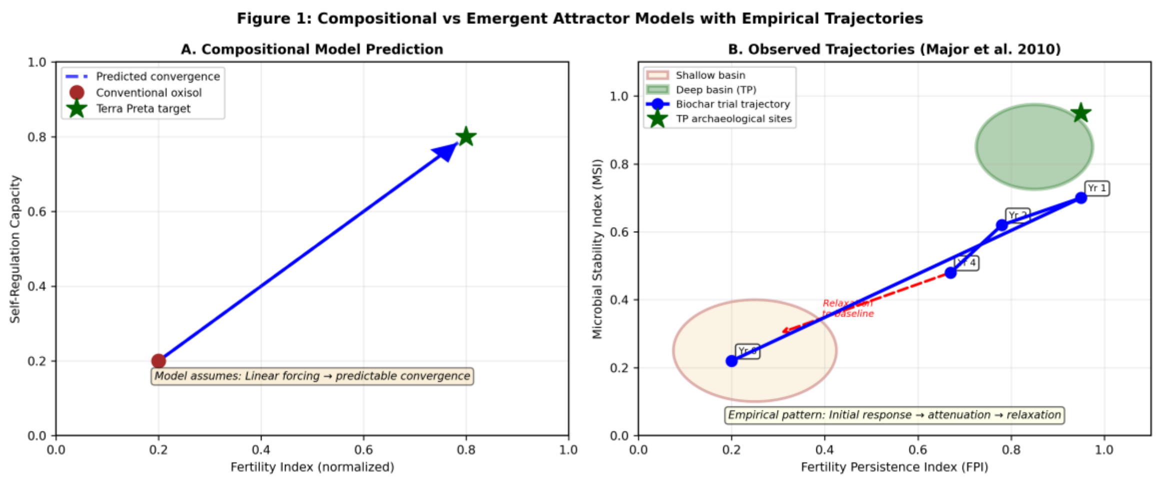


Figure 2. Terra Preta System Architecture. Integrated components and feedback loops: aged biochar with surface oxidation (CEC 60–80 cmol/kg; Cheng et al., 2006), mineral integration, oligotrophic microbial regulation (OTU richness 396 vs. 291; Kim et al., 2007), CUE increase 10–30% (de Graaff et al., 2010), charcoal heterogeneity 20–50% (Neves et al., 2003).

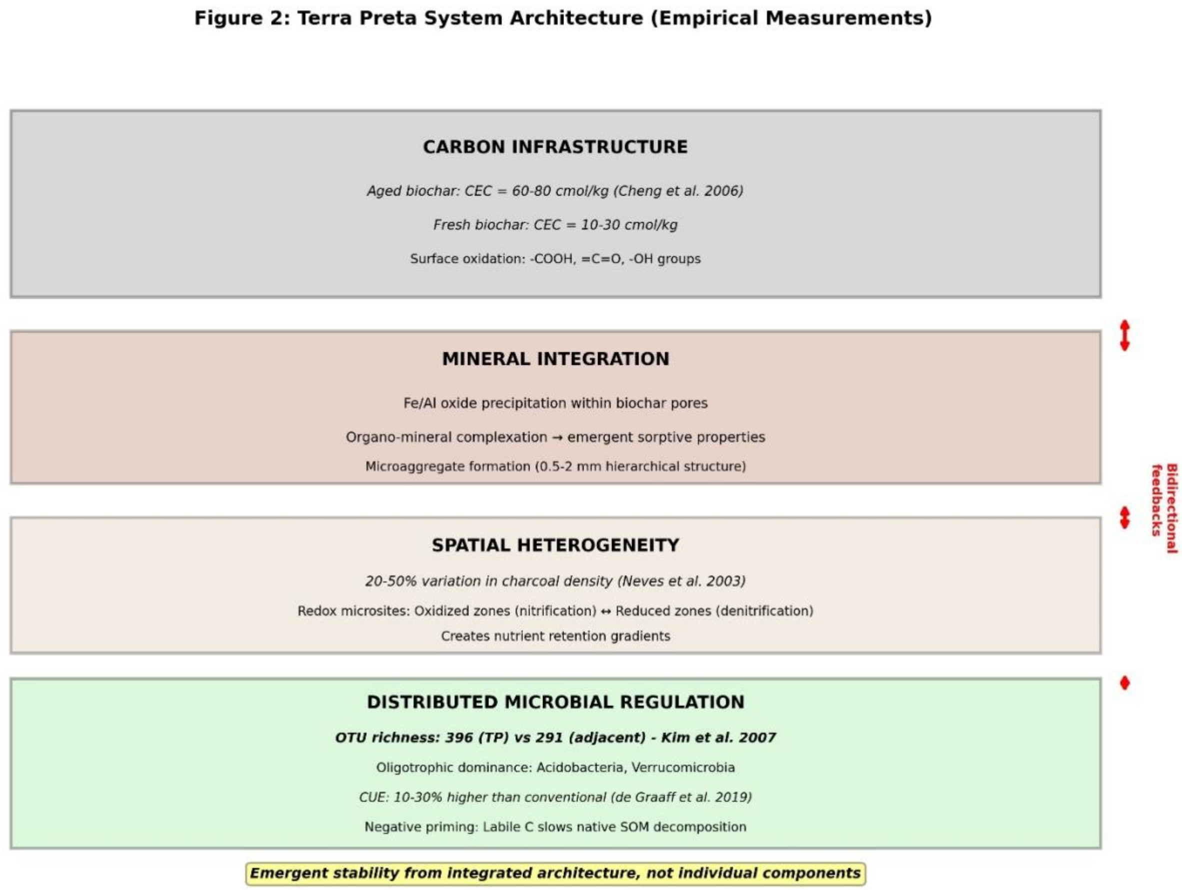


Figure 3. Conceptual Synthesis of Long-Term Biochar Trajectories (schematic / illustrative). Synthesis from Jeffery et al. (2017), Jiang et al. (2024), and Yang et al. (2025). Conceptual synthesis, not a statistical meta-analysis.

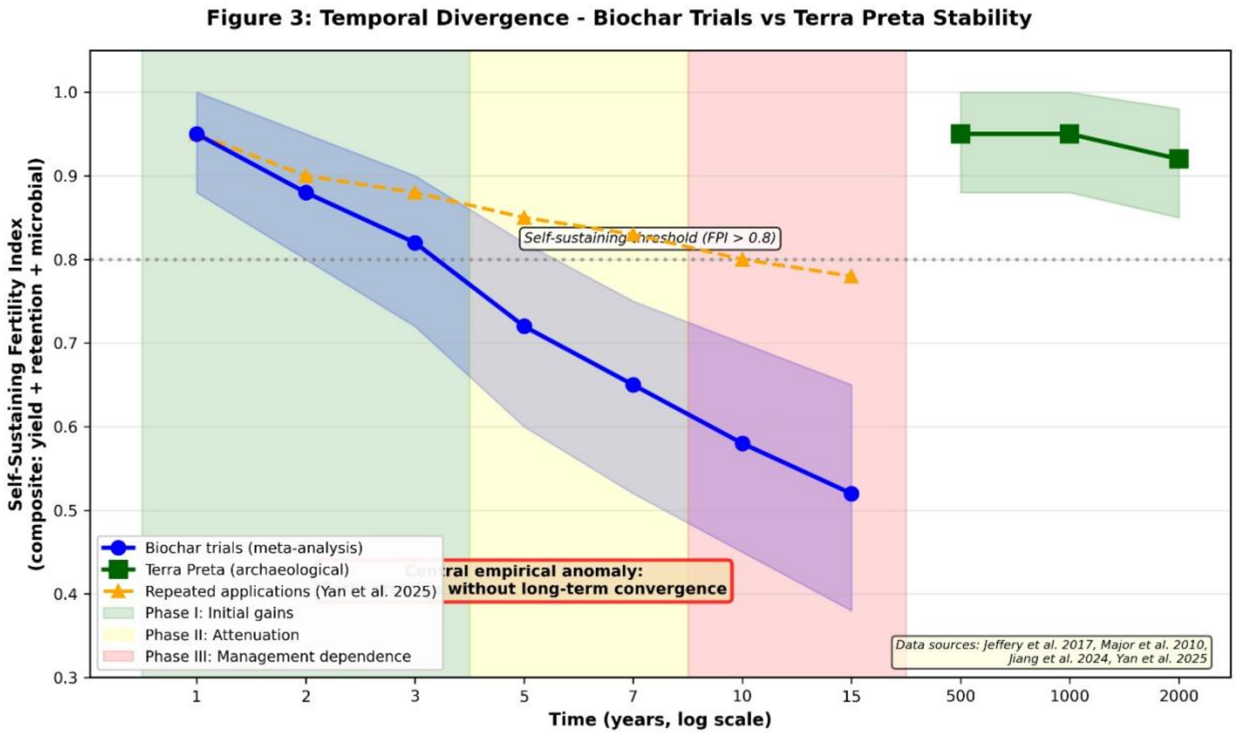


Figure 4. Operationalized Attractor Dynamics Simulation (schematic / illustrative). Panel A: Asymmetric double-well potential. Panel B: Basin stability. Panel C: Forced transition versus resistance. Panel D: Hysteresis pathway. Parameter values are illustrative.

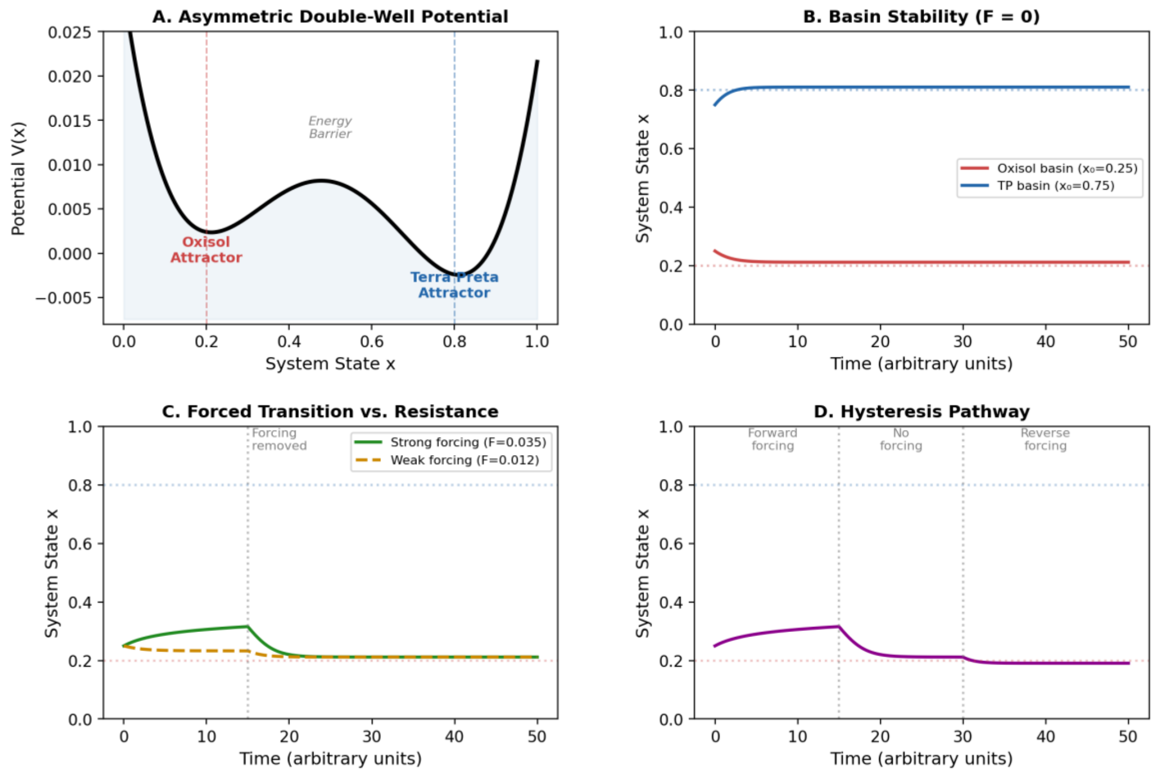
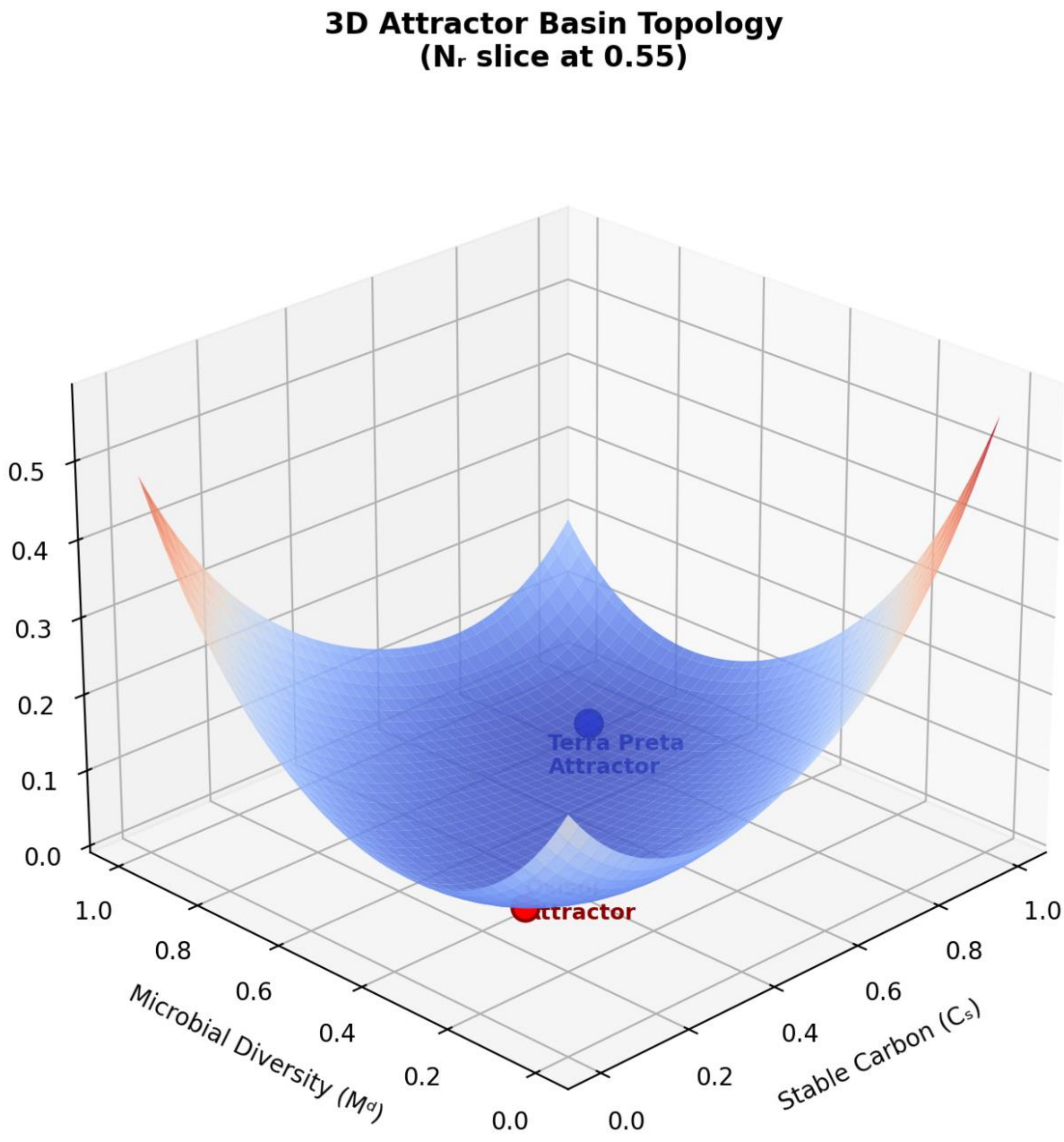


Figure 5. Three-Dimensional Attractor Basin Topology. Surface plot of potential V(S) over the C_s–M_d plane at fixed N_r = 0.55.



Box 2: Glossary of Dynamical Systems Terms

Attractor: A state or set of states toward which a dynamical system evolves from nearby initial conditions under its endogenous dynamics. Operationally: the soil configuration to which the system returns after perturbation.

Basin of attraction: The set of all initial conditions from which a system evolves toward a given attractor. Operationally: the range of soil states from which recovery to the stable configuration occurs without external forcing.

Hysteresis: Path-dependent asymmetry in system response: the trajectory from state A to state B differs from the reverse trajectory. Operationally: degradation of Terra Preta and attempted restoration follow different pathways requiring different forcing magnitudes.

Multistability: Coexistence of two or more stable states (attractors) within the same system under identical external conditions. Operationally: the same climate and parent material can support either oxisol or Terra Preta configurations.

Path dependence: Sensitivity of long-term system state to the historical sequence of inputs and perturbations, not merely their cumulative magnitude. Operationally: identical total inputs applied in different temporal sequences produce different soil outcomes.

Threshold transition: A critical forcing magnitude beyond which the system shifts discontinuously from one attractor basin to another. Operationally: the amendment intensity below which only transient displacement occurs.

Basin depth: The integrated resistance force from equilibrium to the basin boundary; a measure of attractor stability. Operationally: the magnitude of sustained disturbance required to induce irreversible state collapse.

Declaration of 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 (CRediT)

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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During the preparation of this work the author used AI assisted tools to support content organization and language refinement. All output was reviewed, verified and edited by the author, who takes full responsibility for the final content.

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Appendices

Appendix A: Supplementary Data Synthesis

Study / System	Duration	FPI Est.	CSR Est.	MSI Trend	Trajectory Class
Major et al. 2010	4 yr	~0.7	Declining	Low	Attenuating; fertilizer-dependent by yr 4
Jeffery et al. 2017	1–5 yr	0.9–1.0	Stable	Rising	Short-term positive; no convergence data
Gross et al. 2024	12–14 yr	~0.4–0.6 (sandy soils; higher in loam)	Declining (sandy)	Not reported	SOC dissipation in sandy soils
Yang et al. 2025	4–12 yr	~0.7–0.9	Stable w/ reapp.	Moderate	Benefits require re-application
Schmidt et al. 2021	Variable	Variable	Variable	Variable	Positive but context-dependent
Archaeological TP	500–2000+ yr	0.8–1.0	High (stable)	High	Self-sustaining; no management required

FPI values estimated from reported yield trajectories. CSR from reported SOC stocks. MSI trends inferred from microbial data where available.

Appendix B: Extended Quantitative Framework

The state vector S(t) = {C_s, C_m, M_d, N_r, H, R} provides a multidimensional representation: C_s (stable carbon, BPCA markers, g C/kg); C_m (microbial biomass carbon, fumigation-extraction, mg C/kg); M_d (microbial diversity and functional redundancy, Shannon diversity + functional gene arrays, dimensionless); N_r (nutrient retention efficiency, proportion retained after rainfall simulation, 0–1); H (structural heterogeneity, CV of C_s across cm-scale cores, dimensionless); R (resilience coefficient, return rate after perturbation, $year^{-1}$). Basin depth D is estimated by integrating resistance force over perturbation magnitude.

Appendix C: Long-Term Biochar Trial Chronosequence

Study	Duration	Soil Type	Biochar Rate	Key Outcome	TP Convergence?
Major et al. 2010	4 yr	Savanna oxisol	8–20 Mg ha^{-1}	Yield gains yrs 1–2; fertilizer-dependent by yr 4	No
Jeffery et al. 2017	1–5 yr	Multiple (meta)	Variable	+10–25% yield; tropical > temperate	No long-term data

Gross et al. 2024	12–14 yr	Sandy / loamy	31–40 Mg ha^{-1}	Sandy: SOC dissipated; loamy: stable	No
Seyedsadr et al. 2022	Variable	Multiple (meta)	Variable	Long-term effects on soil properties	No unmanaged persistence
Yang et al. 2025	4–12 yr	Multiple	Annual re-app.	Benefits sustained under re-application	Benefits require re-application
Schmidt et al. 2021	Variable	Multiple (review)	Variable	Positive but variable	No full TP replication

Appendix D: Proposed Experimental Protocols

Protocol 1 (Resistance): Minimum 3 authenticated Terra Preta sites with adjacent controls. Factorial biochar rate (0 Mg ha^{-1}, 10, 20, 40 Mg ha^{-1}) × organic amendment × mineral enrichment. Duration: 15 years minimum. Required: minimum 4 replicate plots per treatment; spatial heterogeneity addressed through stratified sampling across within-site variability gradients; power analysis recommended before trial initiation to ensure adequate detection of convergence thresholds.

Protocol 2 (Hysteresis): Minimum 2 authenticated sites. Graduated disturbance (0–75% annual biomass removal, 5 years) + 10-year recovery. Required: minimum 3 replicates per disturbance level; paired sampling across topographic positions to control for spatial heterogeneity; statistical power sufficient to detect >20% divergence in recovery trajectories.

Protocol 3 (Assembly dependence): Amendment order (carbon-first, mineral-first, simultaneous) × temporal spacing (pulse, monthly, continuous). Duration: 10 years. Required: minimum 3 independent site replications to control for edaphic variation; within-site replication of minimum 4 plots per treatment combination.

Protocol 4 (Oligotrophic regulation): Terra Preta under oligotrophic maintenance versus copiotrophic forcing (high-NPK). Monitor persistence following withdrawal at year 5. Duration: 15 years. Required: minimum 3 sites spanning geographical range of documented Terra Preta; spatial heterogeneity quantified through geostatistical sampling design.

Protocol 5 (Engineered consortia): Biochar-amended soil receiving designed oligotrophic consortia versus controls, management withdrawal at year 5. Duration: 15 years post-withdrawal. Required: minimum 3 soil types to assess generalizability; sample sizes sufficient for community composition analysis at >95% sequence coverage.