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Distance and age: Toward a mechanistic model of spatio-temporal soil response to agroforestry trees

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Abstract

Whether trees in agroforestry systems improve nearby soil has been assessed along two separate axes distance-from-tree spatial gradients and tree- or system-age chronosequences studied as distinct literatures that rarely engage one another. This review integrates both bodies of evidence, drawing on 95 primary studies identified through a documented landscape-scan process, to ask one question: does the mechanism generating the distance-from-tree soil gradient shift identity as the system ages and can that shift explain why gradient existence, direction and magnitude are reported so inconsistently across the literature? The evidence shows that gradient direction and existence are not universal, that age trajectories are not always monotonic, that different soil-property classes can diverge within the same site and that the two literatures are drawn from geographically decoupled contexts. This review proposes as a hypothesis, not an established finding a three-mechanism handoff in which root-zone competition, litterfall-zone organic input and canopy-microclimate modulation contribute in different proportions as a system ages; the canopy-microclimate component has no direct supporting evidence in this database. Evaluated individually against seven documented contradictions in the primary literature, the hypothesis explains one directly, partially explains three and leaves three unresolved, including an age-climate confound the evidence base cannot separate.

Keywords: Soil organic carbon, distance-from-tree gradient, chronosequence, root-zone competition, litterfall, canopy microclimate

1. Introduction

Soil conditions beneath and around a tree differ from those in the surrounding matrix and that difference is neither fixed in space nor constant over time it changes with distance from the trunk and again as the tree and its stand age. This joint spatial and temporal variability is a defining, if under-examined, feature of how trees shape soil, driven principally by root activity and litter deposition, with canopy-level microclimate effects proposed as a further, less directly evidenced contributor. In agroforestry systems, this capacity for soil modification underlies much of what is claimed about the practice's effect on soil and it is assessed almost entirely through a single physical interface the soil under and around the tree whose apparent response depends on where and when, in the tree's life that soil happens to be sampled.

Two research traditions have developed around this interface without meaningfully engaging one another. Spatial-gradient studies sample soil carbon, nutrients, aggregate structure and microbial community composition at increasing distance from the trunk, treating the tree as a stationary source of influence on the surrounding soil. Chronosequence studies instead hold distance from the tree roughly constant and vary stand age, asking whether decades of tree presence produce a soil legacy that accumulates, plateaus, or reverses. Each design isolates its own axis effectively and has produced an internally consistent body of findings, but neither, by construction, can address whether the two axes interact whether the process generating a gradient in a young system is the same process generating it, or failing to, decades later.

The consequence is that a null gradient reported at one site and a pronounced gradient reported at another are often read as competing findings about a single, stable phenomenon, when they may equally be accurate reports on two different phenomena, sampled at different points along a trajectory neither literature was designed to trace.

Distinguishing a genuine absence of soil response from an observation simply mistimed relative to that shared trajectory requires reading the spatial and temporal evidence together as one connected record an integrative, mechanistic synthesis that quantitative pooling across studies is not designed to provide.

Existing quantitative syntheses of agroforestry soil science have already established a good deal along these lines. Several meta-analyses report that agroforestry systems, aggregated across sites, tend to increase soil organic carbon (SOC) relative to conventional cropland or pasture (Ivezić *et al.*, 2022; Shi *et al.*, 2018; Mayer *et al.*, 2022) ^[1, 2, 3], and a global synthesis of the pathway linking tree biomass to soil carbon accumulation has clarified how much of that increase can plausibly be attributed to direct carbon transfer rather than other routes (Ma *et al.*, 2020) ^[4]. A systematic map has catalogued the broader range of ecosystem services associated with agroforestry adoption, extending well beyond soil carbon into biodiversity, yield, and livelihood outcomes (Castle *et al.*, 2022) ^[5], and a recent systematic review has synthesized how tree structural features shape hydrophysical soil properties within European agroforestry systems specifically (Mitrová *et al.*, 2025) ^[6]. Collectively, these syntheses answer a specific and important question: whether introducing trees changes soil properties, on average, relative to their absence.

What these syntheses share, however, is a strategy of narrowing scope along a single axis a property, a system type, a climate zone, or an outcome category to make pooling tractable; within that narrowed scope, spatial and temporal structure are treated as simplifying assumptions, not as objects of analysis in their own right. This pattern is not confined to the four syntheses named here: a bias-aware synthesis of meta-analyses (Rubeaud *et al.*, 2026) ^[7] reports that a majority omit stand-age detail entirely. A synthesis restricted to soil organic carbon within alley cropping systems (Ivezić *et al.*, 2022) ^[1] or temperate climates (Mayer *et al.*, 2022) ^[3] narrows along system type or region; one restricted to hydrophysical properties within Europe (Mitrová *et al.*, 2025) ^[6] narrows along property and region together; a systematic map of the full range of agroforestry ecosystem services (Castle *et al.*, 2022) ^[5] trades depth for breadth. Whichever axis is chosen, distance from the tree tends to enter, where it enters at all, as a binary contrast near tree *versus* open field, agroforestry *versus* control nested inside the comparison the synthesis was built to test, not as a continuous gradient in its own right; stand or system age fares similarly, appearing more often as a study-level descriptor than as a trajectory to be analyzed.

Consequently, whether the process generating a spatial gradient at one stage of a system's life is the same process generating it, or failing to, at another has not been addressed within any single existing synthesis, quantitative or systematic each was built to answer a bounded question about one property, one region, or one comparison type, and answered it well. What remains is the question those designs could not, by construction, ask: not whether trees change soil properties on average, but whether the spatial pattern and the temporal trajectory are two expressions of one underlying process, rather than two separate phenomena that happen to share a name the premise this review adopts and the reason a synthesis built around either axis alone cannot supply what is needed here.

Addressing that gap directly means asking, as a single question, how soil carbon, nutrient, physical and microbial properties co-vary with distance from a tree, and whether the relative importance of the mechanisms generating that co-variation shifts systematically as the system around it ages. Posed this way, the question does not privilege either axis: it treats spatial position and system age as two coordinates of one process, to be read together rather than in separate literatures.

Answering it requires attention to several facets of the evidence that have rarely been considered jointly. A distance-from-tree gradient need not behave identically across property classes carbon, nutrients, physical structure and microbial community composition may respond differently, or even in opposite directions, within the same system. The gradient itself may not be a fixed feature of tree presence but an age-dependent one, weak or absent early in a system's life and established only later. The trajectory of change with age is similarly open: soil properties may accumulate steadily over time, or instead rise, plateau, and decline as a stand matures, a pattern with direct implications for how a single spatial snapshot should be interpreted. Underlying all of this is a question of mechanism whether belowground competition near the tree, litter-derived inputs at greater distance, and canopy-mediated microclimate effects operate as distinguishable, competing processes, or as complementary contributions whose relative weight changes with system age. Because the evidence bearing on these questions is unevenly distributed across geography and system type, any answer must also specify how far a pattern established in one context can be expected to generalize to another.

This review's contribution is not a new estimate of the average magnitude of a tree's effect on nearby soil, but a shift in how that effect is conceptualized: from a fixed spatial signature of the tree to a set of interacting, age-contingent processes whose relative influence changes as the system develops. Read from this perspective, the spatial and temporal evidence already available in the literature cease to function as two separate bodies of work answering different questions, and instead become complementary observations of a single, mechanistically structured phenomenon each finding assessed for what it indicates about process and its context-dependence, rather than pooled toward one average effect.

2. Methods

2.1 Review design

This review applies a systematic integrative design: a documented, auditable process of literature identification, selection and verification (Figure 1), combined with narrative, mechanism-based synthesis across the full evidence base rather than a single pooled statistic. Here, "systematic" describes this documented process itself, built on web search and a four-pool search strategy (§2.2) the approach best suited to reading two literatures that have never previously been assessed against each other. The design follows the review's central question whether the mechanism generating the distance-from-tree soil gradient shifts identity as a system ages a question of relative process weight, not average effect magnitude.

The evidence was synthesized using complementary summary tables and a mechanism-based narrative framework that distinguished direct empirical evidence from interpretive inference.

2.2 Literature search and study selection

Literature identification consisted of general web search with the four-pool search strategy shown in Table 1. Search terms were refined empirically across two to six rounds per pool, each round building on what the previous round returned. Forward and backward citation chasing supplemented these searches for a subset of papers and a further set was drawn from an earlier, related evidence-gathering stage of the broader project on topical grounds. Every substantive claim traces to the original peer-reviewed publication.

A study qualified as primary evidence if it reported field-measured soil physicochemical or biological data from an agroforestry, forestry, forest-plantation, silvopasture, alley-cropping, or tree-based intercropping system and used an explicit distance-from-tree spatial design, an explicit tree- or systemage comparison, or both; peer-reviewed conference papers reporting full primary data were treated as equivalent to journal articles. This scope centers the review on primary field measurement, the level at which distance and age effects are actually observed.

Relevance was assessed inline during extraction against these criteria (Figure 1), excluding grey literature thesis, unpublished reports and non-peer-reviewed preprints and conference-abstract-only records by default, keeping the evidence base anchored to peer-reviewed primary data throughout. One entry was retained per underlying dataset, using the most complete or most recent version where the same data appeared in more than one publication. Six studies with a land-use-type or system-boundary design short of a genuine distance or age comparison were retained as contextual evidence: land-use-type comparisons without a distance or age gradient (Masebo *et al.*, 2025; Bastos *et al.*, 2023; Ansari *et al.*, 2024; Aryal *et al.*, 2019, 2022) [8, 9, 10, 11, 12], a grass-dominated buffer study of borderline agroforestry fit (Seobi *et al.*, 2005) [13], and an orchard system at the edge of the review's system-type scope (Zheng *et al.*, 2020) [14].

2.3 Data extraction and quality assessment

Each eligible study was extracted into a structured per-paper record within one of the four thematic evidence files (§2.2), identified by a theme-letter code that supports cross-referencing between the extraction record, Table 1, and the citations used in Results and Discussion. Fields captured consistently covered bibliographic and site descriptors (citation, year, country, climate zone, system and species), design descriptors (age class, distance classes, soil depth increments, variables measured), and interpretive descriptors (main findings, author-stated limitations, and relevance to this review's research questions). Design type, sample size, replication, and statistical approach are recorded wherever recoverable from each source, with coverage varying across the collection (§2.1). Quality assessment, addressed below, was applied as a separate step following extraction. Records were kept as structured markdown tables organized by thematic file.

Verification followed extraction as a sequential check on the pooled collection, applied independently of the identification and eligibility judgments in §2.2, and produced four confidence tiers: roughly twenty citations independently cross-checked against a second source, some fifty-five to sixty judged internally consistent on inspection, about ten partially confirmed with some fields still open, and ten to twelve confirmed only to title or topic level. These tiers guide how individual findings are weighted in synthesis.

Workflow stage

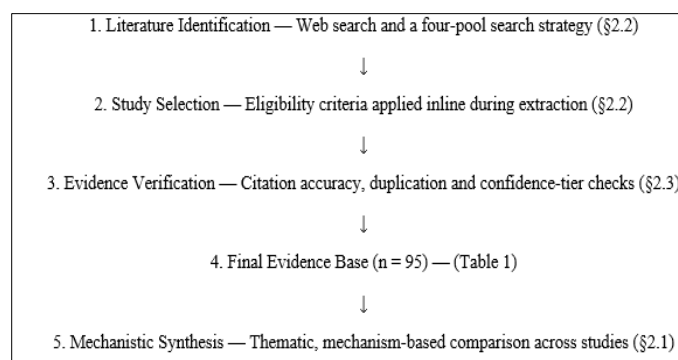


Fig 1: Literature identification and evidence verification workflow

Quality control applies an adapted, field-appropriate set of six considerations design rigor, replication and independence, confounding control, measurement transparency, statistical appropriateness and reporting completeness suited to observational field soil science, guiding qualitative judgment on how individual studies and clusters of studies are weighted in synthesis. Each consideration targets a specific risk in this literature: design rigor and confounding control address site representativeness, replication and independence address shared-site inflation across papers from the same research group, and measurement transparency, statistical appropriateness, and reporting completeness address whether a finding can be checked directly against its own source.

Replication and independence produced the review's clearest finding: six papers from one research group, publishing across several years on the same alley-cropping network, draw on three actual field sites (Beule, 2020, 2021, 2022; Beuschel, 2019; Vaupel, 2023, 2025) [15, 16, 17, 18, 19, 20]. Each paper is retained individually, since each measures different variables or years, but the cluster is treated as roughly three independent spatial replicates wherever it is invoked in synthesis, applied consistently wherever the cluster's papers appear in Results and Discussion so that shared field sites do not inflate apparent consensus. A structurally similar pair (D'Hervilly, 2020, 2021) [21] is carried forward as a single open item pending independent confirmation. Three publications reporting the same underlying dataset under different extraction entries Adiyah *et al.* (2023) [22], Sun *et al.* (2025) [23, 24], and Sutterlütli *et al.* (2023) [25] were merged into single canonical records.

Design rigor is characterized directly for the studies this review draws on most heavily, since these six studies carry a large share of the review's mechanistic argument in Discussion: Pardon *et al.* (2017) [26] offers the strongest replication, spanning seventeen fields across the review's age range; Cardinael *et al.* (2015) [27] and Albert-Black *et al.* (2025) [28] are each single-site, the latter additionally limited to two age classes despite its factorial design; Beuschel *et al.* (2019) [16] belongs to the six-paper German cluster described above. Upson *et al.* (2016) [29] and Kimaro *et al.* (2024) [30] each report comparisons across multiple systems or land-use types, with site-level replication as stated in their own abstracts. These characterizations, applied selectively where the evidence supports a specific, checkable judgment, constitute the quality-control work completed for this review; the six domains function as a lens for these targeted characterizations, not a uniform score computed for every paper.

3. Results

Table 1: Composition of the evidence base by thematic pool.

Thematic pool	Papers (n)	Design focus	Predominant geography
Spatial carbon, nutrients, physical properties	17	Distance-from-tree gradient	Temperate (Europe, North America)
Spatial biological, microbial, root properties	23	Distance-from-tree gradient	Temperate (concentrated in Germany and France)
Temporal tree/system-age chronosequences	30 (22 newly identified + 8 cross-referenced) ¹	Age trajectory	Tropical and subtropical (Africa, Asia, Latin America)
Breadth sweep silvopasture, savanna, plantations	25	Mixed spatial and/or temporal	Geographically mixed
Total	95		

The composition summarized in Table 1 is not geographically uniform across pools: the spatial-gradient literature is concentrated in temperate systems, while the age-chronosequence literature is concentrated in the tropics and subtropics (examined fully in §3.3). The property-class and age-trajectory findings presented in §3.1 and §3.2 below should not be read as drawn from directly comparable geographic contexts.

3.1 Spatial gradients: what the evidence shows

Across the seventeen spatial-gradient studies reporting soil carbon, nutrient, or physical properties, the predominant pattern is higher soil organic carbon and nutrient concentrations closer to the tree, reported across a range of system types and sampling designs (Pardon *et al.*, 2017; Judson *et al.*, 2025; Kindie *et al.*, 2023; Saputra *et al.*, 2020) [26, 31, 32, 33]. This pattern is not unconditional. In the largest single study in this subset, spanning seventeen fields, a significant distance effect on carbon and nutrients was detected in fields fifteen years and older but was absent in fields younger than five years (Pardon *et al.*, 2017) [26]; in a factorial design crossing distance with two tree-age classes, soil carbon stock was eighteen percent greater near seven-year-old trees than at 15 m, while no equivalent distance effect was detected near four-year-old trees (Albert-Black *et al.*, 2025) [28].

Reported gradients are also neither uniform in magnitude across sites nor uniform across properties within the same study. A nine-location replication found the carbon-distance response statistically significant at five of the nine sites (Sauer *et al.*, 2023) [34]. Where multiple properties were measured jointly, they did not necessarily peak at the same distance: carbon and field capacity peaked nearest the tree while phosphorus peaked farther out in one study (Abbasi Surki *et al.*, 2021) [35], and hydrological properties porosity and saturated hydraulic conductivity were reported to differ by hedge age class as well as by position relative to the hedge (Biffi *et al.*, 2026) [36]. Gradient strength was also reported to vary with tree species identity (Mesfin *et al.*, 2022) [37], with the spatial arrangement of trees rather than distance alone (Lunka *et al.*, 2016) [38], and to co-occur with a parallel gradient in fine-root biomass (Wang *et al.*, 2023) [39, 40].

The twenty-three spatial-gradient studies addressing biological and microbial properties show a broadly similar pattern of near-tree enrichment for some outcomes: pathogen-suppression potential (Vaupel *et al.*, 2023) [17], microbiome compositional shift (Vaupel *et al.*, 2025) [18], and denitrification-associated gene abundance (Beule *et al.*, 2020) [15] were each reported to vary with distance from the tree, and a clear, quantified near-tree gradient was reported in a separate, mature, twenty-seven-year-old system (Alagele *et al.*, 2020) [41]. One study reported explicit distance thresholds tree-associated fine roots dominant

to 5.5 m, grassland-associated roots dominant beyond 8.5 m (Sutterlütti *et al.*, 2023) [25] alongside a companion estimate of a 2 m distance-of-influence in a twenty-one-year-old system (Guillot *et al.*, 2021) [42]. This pool also contains the clearest exceptions to a universal-gradient pattern: two independent studies of young systems, five to eight years old, reported no significant within-alley distance effect (Beuschel *et al.*, 2019; D'Hervilly *et al.*, 2020) [16, 21], directly complicating the pattern reported above. A related study reported a stronger distance effect below the topsoil than within it (Beule *et al.*, 2022) [19]. Within-study divergence across taxa or property classes recurs across this pool. One study reported arbuscular mycorrhizal fungi declining with proximity to the tree while other fungal taxa increased over the same transect (Giray *et al.*, 2024) [43]; comparable spatial structuring was reported two decades earlier, predating modern molecular methods (Livesley *et al.*, 2000) [44]. Six of the twenty-three biological/microbial papers draw on the same three field sites, sampled repeatedly by overlapping author teams (Beule, 2020, 2021, 2022; Beuschel, 2019; Vaupel, 2023, 2025) [15, 16, 17, 18, 19, 20] and weighted as roughly three independent replicates wherever invoked (§2.3). A second, structurally similar pair (D'Hervilly, 2020, 2021) [21] remains an open item on the same basis (§2.3).

3.2 Temporal (age) trajectories: what the evidence shows

Among the studies tracking soil properties across tree or system age, the more commonly reported pattern is an increase in soil carbon, nutrient stocks, or microbial biomass with increasing age. A partially resampled Ghanaian cocoa chronosequence spanning three to forty-five years, with a fifteen-year resampling interval, offers one of the few true partial-longitudinal comparisons in this pool rather than a purely cross-sectional one (Adiyah *et al.*, 2023) [22]; a second, independent Ghanaian cocoa chronosequence spanning five to twenty-five years reported a sixteen percent increase in soil organic carbon between its youngest and oldest age classes (Agbeshie *et al.*, 2025) [45]. Comparable increases are reported in an Amazonian cocoa system's deep soil horizons over fifteen years (Suárez *et al.*, 2025) [24], in a four-point poplar-crop chronosequence in subtropical China (three to seventeen years, both biomass and carbon increasing with age; Wang, Z. *et al.*, 2023) [39, 40], and, in the most methodologically complete age-trajectory design in the wider database, in a fifty-year resampling of afforestation chronosequences on former cropland not itself an agroforestry system, but a design template for what a true longitudinal comparison in this literature could look like (Yu *et al.*, 2026) [46]. Further chronosequence studies from Ghana, Ethiopia, India, and elsewhere report broadly consistent increases (Isaac *et al.*, 2005; Demessie *et al.*, 2013; Yadav *et al.*, 2021; Kinyili *et al.*, 2024) [47, 48, 49, 50].

This pattern is not universal. Three independent systems report a non-monotonic trajectory an increase followed by a decline rather than a continued increase with age: nutrient stocks in an alder-cardamom system peaked at fifteen to twenty years and declined by forty years (Sharma *et al.*, 2009)^[51]; a Chinese fir plantation chronosequence found higher soil organic carbon, nitrogen, phosphorus, and microbial biomass at seven years than at fifteen or twenty-five years (Lei *et al.*, 2023)^[52]; and a *Schima superba* plantation chronosequence found soil properties peaking at fifty-five years and declining by sixty-four years (Sun *et al.*, 2025)^[23, 24]. Of these three, only the alder-cardamom system is a true agroforestry system; the other two are forestry plantations, so the non-monotonic pattern is evidenced across tree-dominated systems broadly rather than established as agroforestry-specific. A further study found no significant age effect at all in three of four agroforestry systems examined in Tanzania (Kimaro *et al.*, 2024)^[30], a finding not reconciled by any other result in this subsection. Separately, the same factorial study cited in §3.1 for its spatia findings also reported that the spatial gradient itself was present at seven years and absent at four years (Albert-Black *et al.*, 2025)^[28] direct evidence that the existence of a distance effect, not only its magnitude, can depend on system age.

3.3 Where the two axes remain geographically and structurally decoupled

The two evidence pools that this review draws on are concentrated in different parts of the world. The spatial-gradient

studies cited in §3.1 are drawn predominantly from temperate systems Belgium (Pardon *et al.*, 2017)^[26], France (Cardinael *et al.*, 2015, 2019; Guillot *et al.*, 2021)^[27, 42, 53], Germany (Beule *et al.*, 2020, 2021, 2022; Beuschel *et al.*, 2019)^[16]; Vaupel *et al.*, 2023^[17], 2025), and England (Judson *et al.*, 2025)^[31] among them. The age-chronosequence studies cited in §3.2 are drawn predominantly from the tropics and subtropics Ghana (Adiyah *et al.*, 2023)^[22], Tanzania (Kimaro *et al.*, 2024)^[30], India (Sharma *et al.*, 2009)^[51], and Ethiopia (Demessie *et al.*, 2013)^[48] among them. Only one study in the entire evidence base samples both a distance gradient and an age gradient within the same design: the factorial silvopasture study already cited in both §3.1 and §3.2 (Albert-Black *et al.*, 2025)^[28], and even that study is drawn from a single site.

This is a direct, verifiable feature of the evidence base's own composition, not an inference drawn from it. It means that age and geography and, closely related, system type are close to confounded in this literature: a finding reported as age-dependent in the tropical pool and a finding reported as distance dependent in the temperate pool cannot be assumed to describe the same underlying process operating in two different contexts, because almost no study exists to test whether it does. This is essential context for weighting the patterns established in §3.1 and §3.2 against one another.

Table 2: Documented contradictions across the evidence base.

Tension	Evidence in tension
Gradient existence	Cardinael <i>et al.</i> (2015) ^[27] : no significant distance effect on SOC. vs. Pardon <i>et al.</i> (2017) ^[26] ; Albert-Black <i>et al.</i> (2025) ^[28] ; Abbasi Surki <i>et al.</i> (2021) ^[35] : significant, positive gradients.
Gradient direction	Upson <i>et al.</i> (2016) ^[29] : lower surface SOC under trees than open pasture; reinforced by a herbivore-exclusion study attributing most soil-carbon gain to grasses rather than trees (Wigley <i>et al.</i> , 2020) ^[54] . vs. the majority-positive studies above.
Age-dependence of the spatial gradient	Beuschel <i>et al.</i> (2019) ^[16] : no distance effect in a young system. vs. Pardon <i>et al.</i> (2017) ^[26] : distance effect present in older fields.
Age-trajectory shape	Lei <i>et al.</i> (2023) ^[52] and Sun <i>et al.</i> (2025) ^[23] : non-monotonic, rise-then-decline trajectories. vs. the majority chronosequence pattern of continued increase with age.
Age-effect existence	Kimaro <i>et al.</i> (2024) ^[30] : no significant age effect in three of four systems studied. vs. the general chronosequence literature.
Within-study property/taxon divergence	Rivest <i>et al.</i> (2020) ^[55] : fungal, bacterial, and earthworm gradients point in different directions at the same site. Giray <i>et al.</i> (2024) ^[43] : arbuscular mycorrhizal fungi decline with proximity while other fungi increase. Eldridge and Wong (2005): base cations and phosphorus decline with distance while organic carbon, nitrogen, and sulfur do not. Lira Junior <i>et al.</i> (2020) ^[56] : nitrogen response is distance-independent while carbon response is distance-dependent.
Ecosystem-carbon vs. soil-carbon divergence	Orefice <i>et al.</i> (2025) ^[57] : total ecosystem carbon differs by 43% between silvopasture and treeless pasture, but soil carbon specifically does not differ between them.

3.4 Documented contradictions across the evidence base

Table 2: consolidates seven specific, named disagreements not a general impression of inconsistency, but seven distinguishable ways the primary literature disagrees with itself: whether a gradient or age effect exists at all, whether the spatial gradient's existence depends on system age, the shape an age trajectory takes once established, and internal divergence within single studies. Each entry traces to a specific, real paper in the evidence base, not to an unconfirmed or secondary report, though verification depth varies by paper (§2.3).

These seven tensions are not distributed evenly across the two evidence pools described in §3.3: gradient existence, gradient direction, the age-dependence of the spatial gradient, and within-study property/taxon divergence draw substantially on the temperate spatial-gradient pool, while age-trajectory shape and ageeffect existence draw on the tropical age-

chronosequence pool, and the ecosystem-carbon-versus-soilcarbon divergence stands alone. No single tension in Table 2 is resolved by any other result presented in this section. Establishing that these seven disagreements exist, and are not attributable to fabrication, misreading, or an unverified source, is as far as this section takes them.

The evidence assembled for this review establishes four things empirically: that the distance-from-tree gradient is neither universal in its existence nor consistent in its direction; that age trajectories are similarly inconsistent; that the two literatures documenting these patterns are drawn from largely different geographic and system-type contexts; and that seven specific points of disagreement recur across this evidence base rather than resolving on inspection.

4. Discussion

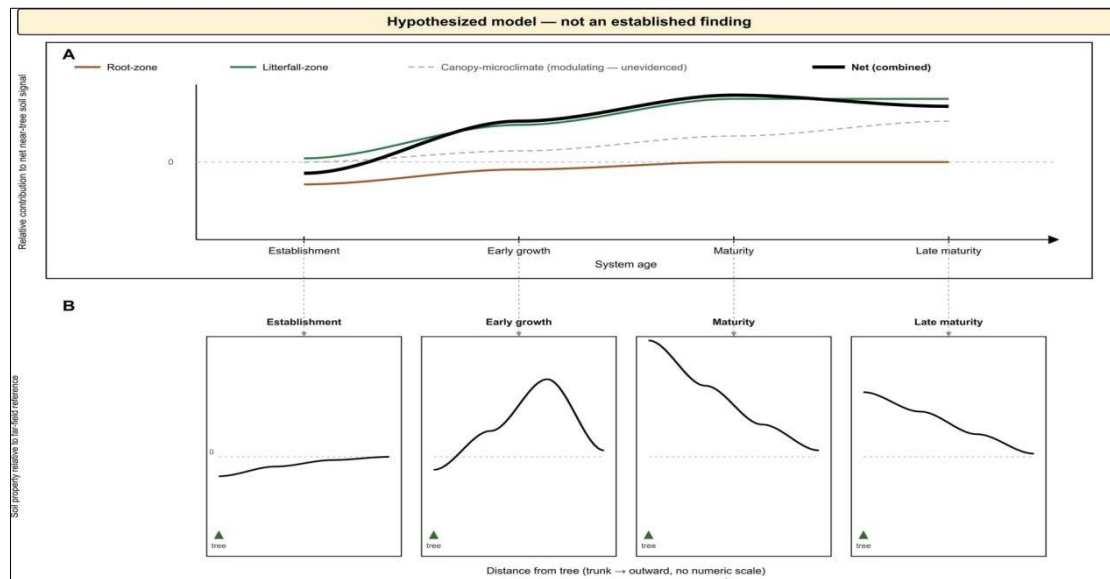


Fig 2: Hypothesized three-mechanism handoff across system age.

4.1 A mechanism-shift hypothesis for spatio-temporal soil variation

Fig 2: sets out the conceptual framework developed from the patterns established in Results: a threemechanism handoff, in which the relative contribution of three zone-generating processes root-zone competition and exudation, litterfall-zone organic input, and canopy-microclimate modulation shifts as a system ages, rather than one fixed process determining a constant tree effect. Each mechanism follows a distinct trajectory: a root-zone curve flat or slightly negative at establishment that declines in relative weight thereafter; a litterfall-zone curve that rises through early growth and plateaus at maturity; and a canopy-microclimate curve acting as a modulating term altering how efficiently litter input becomes stable soil organic matter, rather than contributing a signal of its own. Their combination produces a net curve that dips near zero or slightly negative at establishment, rises through early-to-mid growth, and plateaus or declines at late maturity: a hump-shaped, not continuously increasing, trajectory. This is presented as a candidate explanation for the patterns established in §3.1–§3.4, not a conclusion those results have already proven.

The root-zone component is consistent with the reversed and null gradients documented in §3.1 and Table 2. Root-zone processes are not exclusively depleting: root systems also contribute carbon directly through exudation and fine-root turnover, an enrichment pathway operating alongside belowground competition for water and nutrients. The model treats this component as net-competitive specifically in young, precanopy-closure systems because the one study in this evidence base reporting a root-zone-attributable outcome at that life stage finds net depletion, not because competition is assumed to dominate exudation-driven enrichment more generally; whether this balance holds across other young systems is untested. Trees can produce lower, not higher, near-tree soil carbon than open pasture (Upson *et al.*, 2016)^[29] though the attribution of that outcome to young-system root competition is this review's own inference, not something Upson *et al.* (2016)^[29] themselves establish from a confirmed system age. The hypothesis is further consistent with the age-dependence disagreement already catalogued in Table 2: no significant within-alley distance effect was reported in a young system five to eight years old (Beuschel *et al.*, 2019)^[16], while a significant effect was reported in fields fifteen years and older

(Pardon *et al.*, 2017)^[26], and the same factorial design that found no distance effect at four years found one at seven years (Albert-Black *et al.*, 2025)^[28] the clearest single-study evidence that gradient existence, not only magnitude, can depend on system age. Beuschel *et al.* (2019)^[16] is weighted here as elsewhere one of three independent site-level observations, not one of six (§2.3).

The litterfall-zone component is consistent with the majority pattern reported in §3.1: higher soil carbon and nutrient concentrations closer to the tree in moderate-to-older systems (Pardon *et al.*, 2017; Judson *et al.*, 2025)^[26, 31], alongside reports of the carbon gradient co-occurring with a parallel gradient in fine-root and litter-associated biomass (Wang *et al.*, 2023; Sutterlütti *et al.*, 2023; Saputra *et al.*, 2020)^[39, 25, 33]. These cooccurrences are consistent with a litter- and root-input-driven enrichment process building as a system matures; they do not, on their own, establish that this process is the cause of the gradients reported, since none of these studies isolates litter input from other concurrent changes as the system ages.

The canopy-microclimate component has no direct support in this evidence base. No paper among the ninety-five reviewed here experimentally isolates a canopy-microclimate effect on decomposition rate or realized soil enrichment; the component is carried into this framework by conceptual lineage from an earlier, general single-tree zone-of-influence model (Rhoades, 1996)^[58], not derived from this review's own primary literature. It is retained in Figure 2 because it is a plausible mechanism consistent with the general ecological logic of tree effects on decomposition, not because any study in this database has tested it directly. This is the framework's least evidenced component and is treated accordingly throughout the remainder of the Discussion.

The hypothesis's account of the plateau-or-decline phase is consistent with the three independent nonmonotonic age trajectories reported in §3.2: nutrient stocks peaking at fifteen to twenty years before declining by forty (Sharma *et al.*, 2009)^[51]; soil carbon, nitrogen, phosphorus, and microbial biomass higher at seven years than at fifteen or twenty-five (Lei *et al.*, 2023)^[52]; and soil properties peaking at fifty-five years before declining by sixty-four (Sun *et al.*, 2025)^[23, 24]. Of these three, only the alder-cardamom system (Sharma *et al.*, 2009)^[51] is a

true agroforestry system; the other two are forestry plantations, so this pattern is evidenced across tree-dominated systems broadly rather than confirmed as agroforestry-specific, and no study in this set directly measures why the decline occurs self-thinning, decomposition catching up with a slowing litter input, or another cause are each plausible but untested by any paper in this database.

Two limits on this hypothesis's scope follow directly from Results. First, because the spatial-gradient and age-chronosequence evidence pools are geographically decoupled (§3.3), with only [Albert-Black et al. \(2025\)](#)^[28] sampling both axes at a single site, whether age itself as opposed to climate or system type, which vary almost in lockstep with age across this evidence base drives the proposed mechanism shift cannot currently be separated from that confound; the hypothesis should be read as describing how these mechanisms might combine within a given context as it ages, not as an established, cross-context finding about age's causal role. Second, this hypothesis does not account for the finding that age had no significant effect in three of four systems examined in one study

([Kimaro et al., 2024](#))^[30]; that finding is not reconciled here and is addressed directly in §4.3.

Taken together, the three-mechanism handoff is consistent with the gradient inconsistency, the nonmonotonic age trajectories, and the age-dependence disagreement documented in Results but consistency is not proof, and at least one component (canopy-microclimate) and one finding ([Kimaro et al., 2024](#))^[30] remain, respectively, unevidenced and unexplained. Which of this subsection's claims rest on direct evidence and which are this review's own proposed inference is set out explicitly next.

4.2 What the evidence can and cannot establish

The hypothesis presented in §4.1 rests on evidence of two different kinds. A small set of claims is directly evidenced by the studies reviewed patterns reported, independently and repeatedly, in the primary data itself. A larger set is this review's own account of why those patterns occur, built from the directly evidenced claims but not itself independently tested by any study in this evidence base. Table 3 states both sets in one place.

Table 3: What the evidence establishes and what this review proposes.

Tier	Claim	Basis
Directly evidenced	Gradient direction and existence are not universal across studies	Enrichment is the majority pattern, but depletion (Upson et al., 2016) ^[29] and a null effect (Cardinael et al., 2015) ^[27] are each independently documented
Directly evidenced	Age trajectories are not always monotonic	Non-monotonic, rise-then-decline patterns confirmed independently in three tree-dominated systems (Sharma et al., 2009 ; Lei et al., 2023 ; Sun et al., 2025) ^[51, 52, 23]
Directly evidenced	Different soil-property classes can diverge, even oppose one another, within the same site	Rivest et al. (2020) ^[55] ; Giray et al. (2024) ^[43] ; Lira Junior et al. (2020) ^[56]
Directly evidenced	Whether the spatial gradient itself is age-dependent is an active, unresolved disagreement in the primary literature	Beuschel et al. (2019) ^[16] vs. Pardon et al. (2017) ^[26]
Proposed by this review	A three-mechanism handoff accounts for the four rows above, with relative mechanism weight shifting as the system ages ⁴	This review's synthesis (§4.1); the canopy-microclimate component has zero directly supporting papers in this evidence base
Proposed by this review	Root-zone competitive depletion is most plausible in young, pre-canopy-closure systems	Decoupled from Upson et al. (2016) ^[29] 's confirmed outcome, which does not itself establish system age
Proposed by this review	The non-monotonic pattern applies to tree-dominated systems broadly, not confirmed as agroforestry-specific	Only one of the three non-monotonic examples (Sharma et al., 2009) ^[51] is a true agroforestry system; the other two are forestry plantations
Proposed by this review	Whether age itself, rather than climate or system type, drives the proposed mechanism shift is untested within a single context ⁵	Only Albert-Black et al. (2025) ^[28] , single-site, samples both the distance and age axes at once (§3.3)
Open, unreconciled exception	No significant age effect was found in three of four systems studied	Kimaro et al. (2024) ^[30] ; not accounted for by this or any hypothesis presented in this review
Methodological caveat	The proposed life-stage sequence is reconstructed from cross-sectional, space-for-time comparisons, not from repeated measurement of the same site over time	Inherited limitation of most of the age-chronosequence literature in this evidence base (§2.3)

The canopy-microclimate component of this hypothesis has zero directly supporting papers anywhere in this review's 95-paper evidence base; it is carried into the model by conceptual lineage from [Rhoades \(1996\)](#)^[58] alone (§4.1). Only one study in this evidence base ([Albert-Black et al., 2025, single-site](#))^[28] samples both the distance and age axes at once; this row's claim cannot currently be tested within a single context using the studies reviewed here (§3.3).

The age/climate/system-type confound and the [Kimaro et al. \(2024\)](#)^[30] exception carry the widest consequences for how the hypothesis should be read. The confound is not a minor caveat alongside the model's other claims it bounds the geographic and system-type scope within which the entire hypothesis can currently be assessed at all. The [Kimaro et al. \(2024\)](#)^[30] exception is not a gap the model has simply not yet addressed it is a specific, named finding the model does not predict and

cannot currently accommodate without weakening its own falsifiability.

Two further claims are worth distinguishing from each other. The root-zone and non-monotonic-pattern hypotheses (§4.1) are narrowed inferences layered on directly evidenced outcomes. The canopy-microclimate component differs from these in kind, not degree: it has no directly evidenced outcome underneath it at all.

Table 2's seven documented contradictions are addressed next against this same tiering; which are accounted for by the hypothesis in §4.1, and which, like [Kimaro et al. \(2024\)](#)^[30], are not.

4.3 Reconciling the field's documented contradictions

Table 2: catalogued seven specific disagreements, each evaluated here individually against the hypothesis presented in §4.1. For each, three questions are asked in turn: does the mechanism-shift hypothesis account for it; if so, how strong is that account; and if not, or only partly, that is stated directly.

Gradient existence. Cardinael *et al.* (2015) [27] found no significant effect of distance (0–10 m) on soil organic carbon in an eighteen-year-old alley-cropping system, against a majority of studies reporting a positive gradient (Pardon *et al.*, 2017; Albert-Black *et al.*, 2025; Abbasi Surki *et al.*, 2021) [26, 28, 35]. The mechanism-shift hypothesis does not account for this well. At eighteen years, past the age range in which Pardon *et al.* (2017) [26] reports significant effects and well beyond the young, pre-canopy-closure window in which root-zone competition is hypothesized to dominate, the model's own logic would predict a positive, litterfall-driven gradient at this system's age the opposite of what was found. A competing, non-mechanistic explanation is at least as plausible: Cardinael *et al.*'s narrow 0–10 m sampling range may simply be too short to capture a gradient that manifests farther out, as it does in Pardon *et al.*'s 30 m design. This review cannot adjudicate between these two explanations with the evidence available.

Category: unresolved

Gradient direction. Upson *et al.* (2016) [29] reported lower surface soil carbon under trees than in open pasture, reinforced by a separate herbivore-exclusion study attributing most soil-carbon gain in a semiarid savanna to grasses rather than trees despite concurrent woody-cover increase (Wigley *et al.*, 2020) [54]. The root-zone component of the hypothesis offers a candidate account for the Upson finding specifically: competitive depletion before canopy closure could plausibly produce lower, not higher, near-tree soil carbon. But Upson *et al.* (2016) [29] does not itself confirm the system's age, so this account rests on an inference this review adds to the original finding, not on something the original study established. The Wigley *et al.* finding is not addressed by the root-zone/litterfall-zone/canopy-microclimate framework at all it concerns which vegetation type (grass *versus* tree) contributes carbon under herbivore exclusion, a source-partitioning question the three-mechanism model, built to describe how a tree's own influence changes with distance and age, was not constructed to answer. Category: partially explained for the depletion outcome itself, conditionally; not for the grass-*versus*-tree carbon-source question.

Age-dependence of the spatial gradient. No significant within-alley distance effect was reported in a system five to eight years old (Beuschel *et al.*, 2019) [16], while a significant effect was reported in fields fifteen years and older (Pardon *et al.*, 2017) [26]. This is the single contradiction the hypothesis accounts for most directly: age-dependent mechanism weighting is precisely the claim the model was built to explain, and this disagreement together with Albert-Black *et al.*'s (2025) [28] within-study confirmation that gradient existence, not only magnitude, tracked age is the evidentiary anchor from which the hypothesis was constructed in the first place. That direct fit should not be mistaken for independent confirmation: a hypothesis built to accommodate a specific pattern will, unsurprisingly, accommodate it. Beuschel *et al.* (2019) [16] carries the same reduced weighting here as elsewhere (§2.3). Category: explained, with that circularity noted.

Age-trajectory shape. Two forestry-plantation chronosequences and one agroforestry chronosequence report a rise-then-decline

pattern rather than a continued increase with age (Sharma *et al.*, 2009; Lei *et al.*, 2023; Sun *et al.*, 2025) [51, 52, 23, 24], against the majority chronosequence assumption of monotonic increase. The hypothesis's net curve, as depicted in Figure 2, does accommodate a plateau-or-decline phase at late maturity, so the shape of this contradiction is consistent with the model. What the model does not supply is a tested account of why the decline occurs in these specific systems self-thinning, decomposition outpacing a slowing litter input, and other candidate explanations are each ecologically plausible, but none is directly measured by any study in this database. Category: partially explained the pattern's existence fits the model's shape; its cause does not have a tested mechanistic account.

Age-effect existence. Kimaro *et al.* (2024) [30] found no significant age effect in three of four agroforestry systems studied in Tanzania. Nothing in the mechanism-shift hypothesis predicts or accommodates this outcome, and no alternative explanation is offered here in its place. Manufacturing a post-hoc account for instance, proposing that some systems reach mechanism equilibrium early would repeat exactly the unfalsifiability problem a framework built to explain any outcome creates, since no evidence in this database currently tests or supports that specific claim. Category: unresolved.

Within-study property and taxon divergence. Fungal, bacterial, and earthworm gradients point in different directions at the same site (Rivest *et al.*, 2020) [55]; arbuscular mycorrhizal fungi decline with proximity to the tree while other fungal taxa increase over the same transect (Giray *et al.*, 2024) [43]; base cations and phosphorus decline with distance while organic carbon, nitrogen, and sulfur do not (Eldridge and Wong, 2005); and nitrogen response is distance-independent while carbon response is distance dependent within the same study (Lira Junior *et al.*, 2020) [56]. That divergence exists is directly evidenced and retained without downgrade (Table 3). The hypothesis offers a conceptually plausible account for why it might exist different property classes could respond preferentially to different zone-processes with different spatial and temporal signatures but this is this review's own extension of the model: none of the four studies above examines whether the specific taxa or properties that diverge map onto root-zone, litterfall-zone, or canopy-microclimate influence, only that divergence occurs. Category: partially explained the existence of divergence is established; its attribution to differential mechanism sensitivity is plausible but untested.

Ecosystem-carbon *versus* soil-carbon divergence. Orefice *et al.* (2025) [57] found total ecosystem carbon differing by forty-three percent between silvopasture and treeless pasture, while soil carbon specifically did not differ between them. This contradiction falls largely outside the hypothesis's intended scope. The three-mechanism model describes how a tree's influence on soil properties is expected to vary with distance and age; it makes no claim about the partitioning of carbon between aboveground biomass and soil, which is what Orefice *et al.*'s finding concerns. Extending the model to cover this question would require a component it does not currently have. Category: unresolved.

Collectively, these contradictions indicate that variability in the distance-from-tree soil gradient reflects context-dependent ecological processes rather than inconsistency in the evidence base itself.

4.4 Methodological implications for future study design

The two limits identified in §4.2 and §4.3 point to a specific study design that would actually test the hypothesis, rather than

merely remain consistent with it, as the evidence assembled here does. Testing whether age itself, rather than climate or system type, drives the proposed mechanism shift requires a design that crosses distance and age factorially within a single climate and system-type context, so that age is no longer confounded with the geographic split documented in §3.3. Testing whether the life-stage sequence proposed in Figure 2 reflects a real trajectory, rather than an artifact of comparing different sites of different ages, requires true longitudinal resampling of the same site over time rather than the crosssectional, space-for-time comparisons that make up most of the age-chronosequence evidence in this review.

Partial templates for both already exist in this evidence base, though neither combines them. *Albert-Black et al. (2025)*^[28], already the sole study in this review crossing both axes, offers the closest existing template for the first requirement, but with only two age classes and a single site; a multi-site replication spanning more age classes within one climate and system type would test the hypothesis's central claim directly, rather than relying on it being merely consistent with an evidence base assembled for other purposes. A fifty-year resampling of afforestation chronosequences on former cropland, cited in §3.2 as methodologically the strongest age-trajectory design in the wider database despite not being an agroforestry system itself, offers a template for the second requirement: true repeated measurement of the same site rather than inference across different ones. Neither template addresses the canopy-microclimate component directly; testing it would require a design capable of isolating microclimate effects from litterquantity effects at the same site, which no study reviewed here attempts.

This is the shape such a design would need to take, not a fully elaborated research agenda.

5. Conclusion

Whether agroforestry trees improve soil quality nearby has no single answer in this literature, not because the evidence is too scattered to interpret, but because the question conflates two things this review has treated separately throughout: where soil is sampled relative to the tree, and how long the system has existed. Read as two independent questions, as the field has largely read them, the resulting evidence looks like unresolved noise: some studies find enrichment near the tree, some find none, one finds depletion, and age trajectories rise, plateau, or decline depending on which system is examined. Read together, as this review has attempted here, the same evidence is consistent with a gradient that is not a fixed signature of tree presence at all, but the visible output of a set of mechanisms whose relative weight changes as the system ages a hypothesis this review proposes, not one it has proven, and one that leaves real, named gaps in what it can currently explain.

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