

Shade tree species richness and functional composition shape soil dynamic independently of tree density in cocoa agroforestry systems: A systematic review and meta-analysis

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Abstract

Agroforestry is increasingly promoted as a nature-based solution to address the intertwined challenges of climate change, biodiversity loss and food security. In tropical cocoa-producing regions, declining soil fertility and agroecosystem resilience driven partly by deforestation and monoculture expansion have intensified interest in shade tree diversification as a strategy for sustaining soil nutrient dynamics. However, the extent to which shade tree diversity and functional composition regulate soil properties remains poorly quantified. We synthesized global evidence on these relationships in cocoa agroforestry systems using multilevel meta-analytic models. Shade tree species richness was positively associated with soil total nitrogen, with effects strengthening under higher deciduous species proportions and remained significant after accounting for shade density, which itself showed an independent negative association with soil nitrogen. Non-linear relationships were observed for soil organic carbon and available phosphorus, with benefits increasing at low to intermediate richness levels before plateauing. No consistent richness effect on soil potassium was detected, though sensitivity analyses revealed opposing marginal associations between richness and density that partially suppressed each other in simpler models. The association between richness and reduced soil bulk density could not be separated from co-variation with shade tree density and should not be interpreted as an independent diversity effect. Overall, soil nutrient responses to species richness were nutrient-specific, frequently non-linear, and shaped by functional composition. Species richness alone is an insufficient predictor of soil nutrient dynamics, and shade tree density and functional composition must be considered alongside diversity when designing cocoa agroforestry systems for sustained soil fertility.

1 Background

The world is currently confronted with a triple challenge: averting climate change, halting and reversing biodiversity loss and supporting the well-being of a growing population (Baldwin-Cantello et al., 2023). Agricultural expansion remains a major driver of these challenges and contributes to soil fertility decline and land degradation in many regions (Tan et al., 2005). In tropical landscapes, the rapid expansion of globally traded commodities has accelerated deforestation and ecosystem degradation (Laurance et al., 2014; Newton et al., 2013). Cocoa cultivation, for example, has been identified as an important driver of forest loss in the major cocoa producing regions (Abou Rajab et al., 2016; Acheampong et al., 2019; Kalischek et al., 2023; Renier et al., 2025). To address the triple challenge, therefore, requires land-use systems capable of reconciling agricultural production with ecosystem conservation and climate resilience (Gawdiya et al., 2025; Willett et al., 2019). Agroforestry has been widely proposed as a nature-based solution capable of addressing these challenges simultaneously – not only by reducing pressure on natural forests, but by actively restoring soil fertility and supporting nutrient cycling within agricultural landscapes (Jose, 2009; Telwala, 2023; Waldron et al., 2017). By integrating trees within agricultural landscapes, agroforestry can enhance biodiversity, regulate microclimates, store carbon, and sustain ecosystem services on which long-term productivity depends (Kala, 2025; Torquebiau, 2024; Waldron et al., 2017).

Soil degradation remains a critical constraint in many tropical commodity production systems. Long-term cultivation, nutrient export through harvest, and limited replenishment of organic matter frequently lead to declining soil organic carbon and nutrient availability (Fontes et al., 2014; Tan et al., 2005). In cocoa-producing regions in particular, soils are often highly weathered and inherently nutrient-poor, making sustained productivity dependent on maintaining soil organic matter and efficient nutrient cycling. Within perennial crop systems, such as cocoa and coffee, agroforestry has long been practised through the use of shade trees that aim to regulate microclimate, support crop establishment and maintain soil fertility (Hernández-Núñez et al., 2024; Hosseini Bai et al., 2017; Vaast and Somarriba, 2014). Shade trees can influence soil processes through several mechanisms. Litterfall and root turnover contribute organic matter inputs, while decomposition processes return nutrients to the soil and support nutrient cycling (Dawoe et al., 2010; Fontes et al., 2014; Hartemink, 2005). Root systems may also enhance soil structure and influence belowground microbial activity, which in turn affects nutrient availability (Beule et al., 2022; Isaac and Borden, 2019).

Despite these benefits, shade trees are frequently removed or only included at low densities in many cocoa landscapes in favour of full-sun monocultures aimed at maximizing short-term yields (Bisseleua, 2009; Siebert, 2002; Steffan-Dewenter et al., 2007). Simplification of agroforestry systems can reduce litter inputs, alter nutrient cycling processes, and accelerate soil degradation (Nesper et al., 2019; Steinfeld et al., 2023). Moreover, the effectiveness of agroforestry systems in maintaining soil fertility depends strongly on how they are designed and managed, including species composition, tree density, and management practices (Bos et al., 2007; Morales-Belpaire et al., 2025). Understanding how different configurations of shade trees influence soil processes, therefore, remains critical for improving the sustainability of tropical agroforestry systems.

Cocoa agroforestry systems provide a useful case for examining how agroforestry design influences soil fertility and ecosystem functioning (Schroth et al., 2016; Wartenberg et al., 2017). Cocoa is typically cultivated in humid forest regions on often weathered and nutrient-poor soils because of intensive farming practices or previous farming practices, making long-term productivity heavily dependent on the maintenance of soil organic matter and nutrient cycling processes (Asigbaase et al., 2021; Kongor et al., 2019; Wessel, 2015). In many cocoa-producing regions, particularly in West Africa, cocoa expansion has historically involved forest conversion followed by progressive soil nutrient depletion under continuous cultivation. Farmer inputs such as synthetic fertilizers can partially offset nutrient losses but are often insufficient to maintain long-term soil fertility under continuous cocoa cultivation, particularly among smallholder farmers who face financial constraints. As soil fertility declines, farmers frequently clear new forest areas in search of more fertile soils, further exacerbating the deforestation as forests are cleared to establish new farms (Asigbaase et al., 2021). As cocoa ages, soil fertility often declines due to sustained nutrient export through harvested beans, reduced organic matter inputs in full-sun monocultures or simplified systems, erosion following canopy removal, and limited external nutrient replenishment (Amponsah-Doku et al., 2022; Snoeck et al., 2016). Declines in soil organic carbon, nitrogen availability, and exchangeable base cations have been documented across cocoa systems (Amponsah-Doku et al., 2022; Snoeck et al., 2016), with particularly pronounced degradation observed in

older monocultures or intensively managed systems (Arthur et al., 2022; Hartemink, 2005; N'Guessan Diby, 2024). Even where light and water availability are adequate, declining soil fertility can become a major constraint on long-term cocoa productivity and farmer livelihoods (Isaac et al., 2007).

Although cocoa agroforestry has been widely promoted as a strategy for improving sustainability (Schroth et al., 2016; Wartenberg et al., 2017), considerable uncertainty remains regarding how these systems should be designed to optimize ecological processes such as soil nutrient cycling. For instance, it remains unclear how the traits of shade trees rather than shade cover alone shape nutrient return through litter inputs and decomposition. Key uncertainties include the relative importance of leaf phenology versus litter quality in driving organic matter accumulation, whether nitrogen-fixing species consistently enhance soil nitrogen availability across contrasting soil and climate contexts, and how trait composition within diverse shade tree systems interact to influence nutrient cycling outcomes (Dawoe et al., 2010; Fontes et al., 2014; Sari et al., 2022; Wartenberg et al., 2020). Much of the existing research on cocoa agroforestry has focused on structural characteristics of agroforestry systems, such as shade cover, shade density, and broad typological classifications such as simple, intermediate, or complex agroforests (Blaser et al., 2017; Blaser-Hart et al., 2021; Niether et al., 2020). While these metrics provide useful information on system structure, they may not fully capture the ecological mechanisms through which shade trees influence soil nutrient dynamics (Abou Rajab et al., 2016; Asare et al., 2019).

Research from biodiversity-ecosystem functioning (BEF) studies suggests that traits can help explain variation in ecosystem processes beyond species diversity alone, which may act as a coarse proxy for functional differences among species (Hooper et al., 2005; Schwarz et al., 2021; Tobner et al., 2014). As a result, there have been increasing calls to adopt trait-based approaches when choosing shade trees in cocoa agroforestry research (Abdulai et al., 2023; Addo-Danso et al., 2024; Isaac et al., 2024; Sauvadet et al., 2020). This is increasingly tractable, as standardized trait datasets are now widely available and accessible for a broad range of tropical tree species, lowering a previous barrier to trait-based research in agroforestry context (Lusk et al., 2026). Traits such as leaf phenology, nitrogen-fixing ability, and litter quality may influence nutrient cycling, soil organic matter accumulation, and crop productivity, potentially explaining the variability observed among agroforestry systems (Edelstein et al., 2025; Isaac et al., 2024; Sauvadet et al., 2020). Despite growing interest in trait-based approaches, there remains a limited quantitative synthesis of how shade tree species richness and trait composition influence soil processes in cocoa agroforestry systems (Díaz and Cabido, 2001). Existing reviews are largely qualitative or narrative in nature (Isaac et al., 2024), while quantitative syntheses have primarily compared full-sun monocultures with agroforestry systems more broadly without examining specific shade tree traits or species richness explicitly (Niether et al., 2020). As a result, important questions remain regarding how traits and species richness interact to influence different soil nutrient properties outcomes in cocoa agroforestry. It remains unclear which traits matter most for improving soil nutrient status, how environmental and management contexts (soil type, climate, farm age and tree density) shape these outcomes, and whether observed effects are linear, non-linear, or mediated (Cardinale et al., 2012; Hooper et al., 2012).

1.1 Objective of the review

Against this background, this systematic review and meta-analysis aims to synthesize and quantitatively assess existing evidence on the effects of shade tree species richness and traits composition on soil nutrient properties in cocoa agroforestry systems. Specifically, the study addresses the following questions, each paired with a directional hypothesis:

RQ1

What are the effects of shade tree species richness on soil nutrient properties in cocoa agroforestry systems?

H1: We hypothesize that the effects of shade tree species richness on soil nutrient properties will be positive but non-linear, with benefits diminishing or reversing at higher richness levels. This is predicted on the basis that complementarity effects among species are likely to saturate as niche overlap increases at higher diversity, a pattern documented in BEF research more broadly (Wang et al., 2022).

RQ2

What are the effects of composition of shade tree leaf phenology and nitrogen-fixing ability traits on soil nutrient properties in cocoa agroforestry systems.

H2: We hypothesize that trait composition particularly leaf phenology and nitrogen fixing ability will better explain variation in soil nutrient status than species richness alone, reflecting the functional mechanisms through which shade trees influence nutrient cycling (Addo-Danso et al., 2024; Edelstein et al., 2025; Sauvadet et al., 2020).

2 Methods

Full detail of the review protocol, including search strategy, eligibility criteria, screening procedures, and critical appraisal, are reported in the registered and published protocol (Limweta et al., 2026). The following sections summarize key methodological decisions and focus on the quantitative synthesis most relevant to interpreting the results, including deviations from the protocol and post-hoc analytical additions made in response to peer review.

2.1 Search strategy and study selection

Searches were conducted in SCOPUS, Web of Science Core Collection and CAB Abstracts (Ovid) using a PICO-based search string combining terms related to cocoa production systems, shade tree diversity and traits, and soil nutrient outcomes (See full string for each database in the protocol). No start date restrictions were applied; searches were limited to English language peer-reviewed publications. Unique records were imported into CADIMA for deduplication (Supplementary materials *Table S 1*). Studies were

screened sequentially at Title and Abstract then at Full text, with inter-rater reliability assessed using Cohen's Kappa (threshold ≥ 0.60) on a randomly selected subset at each stage.

Studies were eligible for quantitative synthesis if they compared cocoa monoculture with at least three shade tree richness levels within the same experiment and reported extractable summary statistics (mean, variance, sample size) for one or more soil properties. Studies relying solely on soil samples collected beneath individual tree canopies rather than plot representative samples were excluded from the species richness analysis, as such designs capture species-specific effects rather than system level soil properties and are not comparable with plot-level measurements. Our search strategy followed the RepOrting Standards for Evidence Synthesis (ROSES) protocol and Collaboration for Environmental Evidence (CEE) guidelines (Haddaway et al., 2018).

2.2 Publication bias

As our meta-analysis uses existing literature, it is important to check for biases, such as only publishing significant results (Bishop and Nakagawa, 2021; Nakagawa et al., 2023). For each response variable (soil properties) we tested for publication bias by following two steps: (i) Use of visual inspections for patterns of asymmetry in a funnel plot of the 'meta-analytic residuals' including all the significant moderators and (ii) using the multi-level model version of Egger's regression by including sampling standard error, SE, as a moderator in the null and a full model containing all the significant moderators to test for funnel asymmetry (Nakagawa and Santos, 2012).

$$y_i = \beta_0 + \beta_1 SE_i + u_{s[i]} + \epsilon_i$$

Where y_i is the observed effect size (log response ration), $SE_i = \sqrt{\nu_i}$ is the sampling standard error for observation i , $u_{s[i]}$ represents one or more random effects terms accounting for clustering (heterogeneity) and ϵ_i is the sampling error with known variance ν_i .

Time-lag bias was tested using the moderator test for year of publication (Koricheva and Kulinskaya, 2019) (Supplementary materials *Figure S 2 – S 9*).

2.3 Data coding and extraction strategy

For each included study, means, standard deviations, and sample sizes were extracted for soil properties and other variables relevant for the analysis. Data reported in figures were extracted using Graph Grabber v2.0.2 (Quintessa Limited). Where studies reported multiple soil depths, only the 0–30 cm or the reported top layer was extracted to ensure comparability. Only the measurements before the last season of the experiment were recorded in cases of repeated measures (Muchane et al., 2020).

2.4 Potential confounders and reasons for heterogeneity

A central concern in interpreting species richness effects is whether observed soil responses reflect diversity per se or co-variation with shade tree density i.e farms with more shade trees tend to have higher species richness, and tree density itself may drive soil property changes independently of

compositional diversity. To address this explicitly, shade tree density (trees ha⁻¹) was extracted from each study whenever reported or derivable from experimental design information. Other potential effect modifiers extracted during data coding included fertilizer application, cocoa farm age, soil type, climatic conditions, sampling depth, and shade tree functional composition (deciduous proportion, evergreen proportion and proportion of nitrogen-fixed species).

2.5 Data analysis and presentation

2.5.1 Effect size

The log response ratio (log RR = ln(T/C)) was used as the effect size metric, where T and C denote treatment and control means respectively, following (Hedges et al., 1999). Each richness level within a study was compared with the corresponding monoculture control and assigned a unique Effect Size ID (ES_ID) nested within a Study_ID, generating a hierarchical data structure that reflects non-dependence among effect sizes from the same experiment. This non-dependence is addressed through the multi-level meta-analytic model framework. To satisfy the assumption of normality and homogeneity of the error variance, we use the natural log of RR (lnRR) for the meta-analysis (Hedges et al., 1999).

2.5.2 Multi-level meta-analysis

All analyses were conducted using the `rma.mv` function in the `metafor` package in R (Viechtbauer, 2010). Multilevel meta-regression models included Study_ID and ES_ID as nested random effects to account for between-study variance and within study non-dependence respectively. Fixed-effects predictors were mean-cantered prior to modelling to reduce multicollinearity and facilitate interpretation of interaction terms. Model estimation used maximum likelihood (ML) for model comparison via AIC and restricted maximum likelihood (REML) for final parameter estimation and inference, with Knapp-hartung adjusted standard deviation errors (test = "t") used throughout to account for uncertainty in variance component estimation.

For each outcome, candidate models were fitted in the following sequence: (1) null model; (2) linear richness model; (3) quadratic richness model where non-linearity was plausible; (4) models adding trait composition moderators (deciduous proportion) and their interactions with richness; (5) sensitivity models adding shade tree density as a covariate. Model selection was based on AIC under ML; the preferred model was the most parsimonious specification within $\Delta AIC < 2$ of the best-supported model.

The multi-level meta-analytic models below are: the linear (1) and non-linear Eq. (2) (Nakagawa et al., 2023).

$$y_i = \beta_0 + \beta_1 X_{1j[i]} + \beta_2 X_{2j[i]} + \beta_3 X_{3j[i]} + u_{Study} + u_{ES} + \varepsilon_i \quad (1)$$

where β_1 is a slope of the moderator (x_1), $x_{1j[i]}$ denotes the value of x_1 , corresponding to the j_{th} study (and the i_{th} effect sizes).

$$y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i}^2 + \beta_3 X_{2i} + \beta_4 X_{3i} + u_{Study} + u_{ES} + \varepsilon_i \quad (2)$$

Where, y_i is the response variable (log RR) for effect size i ; β_0 is the intercept; $\beta_1 - \beta_4$ are fixed-effects coefficients; X_1 represents centred shade tree species richness; X_2 represents centred shade tree density (trees ha⁻¹); and X_3 represents the proportion of deciduous shade tree species, depending on the candidate model. The random terms u_{Study} and u_{ES} account for the between study variation and the dependence among multiple effect sizes within studies, respectively, and ε_i is the sampling error with known sampling variance v_i .

2.6 Deviation from the protocol

Following data extraction, litterfall, litter decomposition and cocoa yield were excluded from quantitative synthesis due to insufficient and inconsistent reporting across studies, precluding robust meta-analysis. The quantitative analysis was therefore restricted to soil property outcomes a deviation from our protocol (Limweta et al., 2026).

The protocol initially targeted shade tree species diversity. However, diversity metrics were reported inconsistently (e.g. varying indices, incomplete data), preventing standardized comparison. We therefore used species richness as a consistent and extractable variable across studies.

Trait data were also rarely reported in these studies. To enable trait-based analyses, shade tree species were classified using the TRY Plant Trait Database (Kattge et al., 2020), assigning leaf phenology and nitrogen-fixing ability. This allowed calculation of species composition and trait proportions for moderator analyses. Supplementing trait data from external databases is consistent with established meta-analytic practice when primary reporting is incomplete (Gurevitch et al., 2018).

Post-hoc sensitivity analyses addressing peer review concerns. Following peer review, post-hoc analytical additions were made that were not pre-specified in the protocol. The correlation between species richness and shade tree density was assessed for each outcome, and sensitivity models including shade tree density as a fixed-effect covariate were fitted and reported alongside primary results. This addition is reported transparently a response to methodological concerns raised during review.

3 Review findings

3.1 Review descriptive statistics

The systematic review identified 53 eligible studies from 14 cocoa-producing countries, (see *included studies*), of which 23 contributed quantitative data to the multilevel meta-analytic synthesis and 30 informed the qualitative synthesis to evaluate the evidence base and gaps.

3.2 Narrative Synthesis: Evaluation of the evidence base.

3.2.1 Geographical distribution

The 53 publications included in this systematic review were from studies conducted in 14 tropical cocoa-producing countries spanning four continents. South America accounted for the largest proportion of studies (41.5%), followed by Africa (30.19%), Asia (16.98%), and North America (11.32%). All the studies were located within the cocoa growing regions, reflecting the global relevance of conducting a systematic review and meta-analysis on the effects of agroforestry design and management on soil properties within cocoa systems.

Table 1
Geographical distribution of studies included in the systematic review and meta-analysis, organized by continent and country. The table presents the number of primary studies per country across four continents.

Continent (total)	Country	Studies
Africa (n = 16)	Ghana	9
	Côte d'Ivoire	4
	Cameroon	3
Asia (n = 9)	Indonesia	8
	Malaysia	1
North America (n = 6)	Costa Rica	4
	Dominican Rep.	1
	Mexico	1
South America (n = 22)	Brazil	8
	Colombia	4
	Bolivia	3
	Ecuador	3
	Peru	3
	Venezuela	1

3.2.2 Shade tree species and traits representation

Within the shade tree species identity cluster included for the meta-analysis, a total of 23 shade tree species were represented. Of these, the majority were deciduous (n = 14), with fewer evergreen species (n = 9). To enable trait comparisons, included studies within this cluster were required to have both deciduous and evergreen species within the treatment structure.

Nitrogen-fixing species were underrepresented, with only five N-fixing shade tree species identified across the studies, and their distribution was uneven across regions and treatments. Despite this, the most frequently reported traits across studies included nitrogen-fixing ability, leaf phenology (deciduous versus evergreen), and farmer-defined use categories such as timber and fruit trees. Most study designs were based on regionally dominant and farmer preferred shade tree species, for example, Cabruca systems, *Hevea brasiliensis* (rubber), and *Erythrina velutina* for Brazil and timber trees such as *Terminalia ivorensis* and *superba*, and *Milicia excelsa* in Ghana, and Cameroon Figure S 3. However, a small subset of studies employed explicit trait-based experimental designs, directly comparing trait categories such as N-fixing versus non-N-fixing species, deciduous versus evergreen species, or timber vs fruit trees.

Figure 3: Shade tree species reported across cocoa agroforestry studies included in the meta-analysis, by country of origin. The Sankey diagram illustrates the distribution of the top 8 most reported shade tree species across eight countries. Each flow connects a country to the shade tree species recorded within studies from the location. Species appearing in more than one country are represented by a shared colour.

3.2.3 Treatments across studies

The experimental approach shows the region of study patterns. Studies from West Africa i.e., Ghana, take the approach of using commonly used shade trees as well as the use of clear diversity measures e.g., Shannon diversity and Species Richness. Studies from Amazonia i.e., Brazil, commonly use shade trees of Rubber (*Hevea brasiliensis*) and *Erythrina velutina*, as well as typologies of Cabruca systems for the high species diversity treatments.

A range of control treatments was identified across the included studies. The most used control was full-sun cocoa monoculture (55%), followed by low diversity cocoa agroforestry systems (19%) and Forest plots (15%). To ensure comparability of the effect sizes, only studies that had cocoa monoculture as control were considered for the meta-analysis, see Fig. 3.

3.2.4 Outcomes measured

Across all 53 articles utilized in this study, there were 39 distinct outcomes identified in relation to nutrient cycling in cocoa agroforestry systems. The number of outcomes measured per article ranged from one to 17. These outcomes were categorised into soil properties (15 outcomes), litter-dynamics (18 outcomes) and productivity outcomes (5 outcomes). Soil biophysical properties were the most consistently measured outcomes across studies. Properties such as soil organic carbon, soil available phosphorus, soil pH and soil total N were the most frequently reported variables. Productivity outcomes were moderately represented in 11 studies measuring five different outcomes, with cocoa yield being the most measured productivity metric, and a small number of studies assessing disease incidences.

In contrast, litter dynamics and nutrient cycling (n = 5 articles) processes were the least studied outcomes. Despite the central role of litterfall, litter decomposition and nutrient release in mediating soil

fertility in agroforestry systems, measurements of these ecological processes were sparse and inconsistently reported across studies.

3.3 Quantitative synthesis: Effects of shade tree species richness and functional composition on soil properties

Overall, shade species richness was associated with changes across several soil properties, although the direction and form of these relationships differed among variables. Soil organic carbon (SOC) and available phosphorus exhibited non-linear (quadratic) responses to increasing species richness, while soil total nitrogen increased with species richness and was moderated by the proportion of deciduous shade tree species. Species richness was also associated with reductions in soil bulk density. In contrast, soil potassium showed no significant relationship with species richness.

3.3.1 Soil total nitrogen (N)

Prior to analysis, species richness and shade tree density were only weakly correlated in the soil N dataset ($r = -0.054$), indicating negligible co-variation between these variables. Including shade tree density as a covariate significantly improved model fit relative to the richness $\times$ deciduous proportion model ($\Delta AIC = 3.95$; $LRT = 5.95$, $p = 0.015$). After accounting for shade tree density, the multi-level meta-regression indicated that the overall moderator model was significant ($F_{4,13} = 6.06$, $p = 0.006$), with no evidence of residual heterogeneity ($QE (df = 13) = 2.31$, $p = 0.999$). Species richness was positively associated with soil total N ($\beta = 0.165 \pm 0.061$ SE, $p = 0.019$) and this relationship became stronger with increasing deciduous tree proportion ($\beta = 0.159 \pm 0.056$ SE, $p = 0.014$). Shade tree density showed a small but significant negative association with soil total N ($\beta = -0.089 \pm 0.036$ SE, $p = 0.028$), whereas deciduous proportion alone was not significant ($p = 0.636$). The weak richness- density correlation in this dataset confirms that the positive species richness effect was largely independent of variation in shade tree abundance (Fig. 6a).

3.3.2 Soil organic carbon (SOC)

Species richness and shade tree density were weakly and non-significantly correlated in the SOC dataset ($r = 0.234$, $p = 0.272$). Including shade tree density as an additional moderator did not improve model fit ($\Delta AIC < 2$), and shade tree density was not a significant predictor of SOC ($p = 0.164$), providing no evidence that the observed richness response was confounded by shade tree abundance. The primary quadratic model was therefore retained as the most parsimonious representation of the data.

Soil organic carbon (SOC) exhibited a non-linear response to shade tree species richness (Fig. 6b), with both the linear ($\beta = 0.032 \pm 0.015$ SE, $t = 2.15$, $p = 0.044$) and quadratic terms ($\beta = -0.004 \pm 0.002$ SE, $t = -2.09$, $p = 0.05$) statistically significant. The fitted model indicated that SOC increased with richness at lower diversity levels, reaching approximately 15% and 27% higher SOC at five and ten species respectively, relative to monoculture systems. Marginal gains declined progressively with increasing richness, with the estimated benefits of adding one additional species declining from approximately 8%

at one species to 4.3% at five species and approaching zero at around 9–10 species. The model suggested a decline beyond this inflection point though this was supported by only six of 25 observations and should be interpreted cautiously (Fig. 6b).

3.3.3 Soil available phosphorus (P)

Species richness and shade tree density were not correlated in the soil available P dataset ($r = -0.130$, $p = 0.575$). shade tree density was not a significant predictor of available P in the model including both variables ($p = 0.830$), and the primary model findings were unchanged after inclusion of shade tree density, confirming that the observed relationship was not confounded by shade tree abundance.

Soil available phosphorus exhibited a non-linear response to shade tree species richness (Fig. 6c). the positive linear richness term ($\beta = 0.160 \pm 0.025$ SE, $p < 0.0001$) and the negative quadratic term ($\beta = -0.018 \pm 0.006$ SE, $p = 0.006$) together indicated that available P increased rapidly with richness before levelling off at higher diversity levels. The positive richness $\times$ deciduous proportion interaction ($\beta = 0.310 \pm 0.099$ SE, $t = 3.13$, $p = 0.007$) indicated that these gains were stronger in systems with higher deciduous proportions, while deciduous proportion alone was not significant ($p = 0.641$). Residual heterogeneity remained significant (QE (df = 15) = 33.97, $p = 0.03$), indicating that additional unmeasured moderators contributed to the between-study variability.

Model predictions indicated that available P peaked at approximately eight species, with mixtures of five and eight species associated with increases of approximately 95% and 142% respectively relative to monoculture systems. Only two observations fell beyond the inflection point, both with low study weights, and the predicted decline at higher richness should therefore be regarded as a model extrapolation rather than an empirically supported trend (Fig. 6c).

3.3.4 Soil potassium (K)

Species richness and shade tree density were moderately but non-significantly correlated in the K dataset ($r = 0.372$, $p = 0.157$). the primary model including richness and deciduous proportions showed no significant richness effect on soil exchangeable K ($\beta = -0.068 \pm 0.040$ SE, $t = -1.71$, $p = 0.113$), with significant residual heterogeneity (QE(df = 12) = 23.170, $p = 0.026$).

When shade tree density was included as an additional covariate, residual heterogeneity became non-significant (QE(df = 11) = 16.99, $p = 0.108$) and the overall model was significant ($F_{4,11} = 3.56$, $p = 0.042$). species richness showed a marginal negative association with soil K ($\beta = -0.107 \pm 0.051$ SE, $p = 0.057$), while shade tree density showed a marginal positive association ($\beta = 0.0029 \pm 0.0016$ SE, $p = 0.097$). Deciduous proportion and its interaction with richness were non-significant across all specification ($p > 0.42$). Given the small dataset (K = 16) and marginal nature of the key coefficients, findings for soil K should be treated as (Fig. 6d).

3.3.5 Soil bulk density

Species richness and shade tree density were strongly and significantly correlated in the bulk density dataset ($r = 0.86$, $p < 0.001$), indicating that studies with higher species richness also tended to have considerably higher shade tree density. The richness-only model indicated that species richness was associated with reduction in bulk density of approximately 2.9% relative to monoculture systems ($\log RR = -0.029 \pm 0.011$ SE, $p = 0.030$; Fig. 7). However, when shade tree density was included as a covariate, neither richness nor density remained significant, consistent with multicollinearity between the two predictors rather than a genuine absence of effects. Residual heterogeneity was significant across both model specifications ($p = 0.002$).

Given the strong richness-density collinearity and small dataset ($K = 12$), the observed association between species richness and reduced bulk density cannot be attributed to richness independently of tree density. These results suggest that increasing that increasing shade tree more broadly e.g whether through higher diversity or greater abundance may be associated with improvements in soil physical structure, but the available data do not permit the independent effects of richness and density to be distinguished (Fig. 7).

4 Discussion

This study addressed the need to better understand how shade tree species richness and traits influence soil nutrient dynamics in cocoa agroforestry systems, particularly in the context of declining soil fertility and broader sustainability challenges. While agroforestry is widely promoted, existing studies have largely relied on coarse metrics, and there has been limited quantitative synthesis of shade tree richness and the effects of traits agroforests (Blaser et al., 2017; Blaser-Hart et al., 2021; Niether et al., 2020). To address this gap, we conducted a systematic review and meta-analysis of available evidence, explicitly accounting for co-variation between species richness and shade tree density across all outcomes. Our results show that shade tree species richness is associated with non-linear increases in soil organic carbon and available phosphorus, and a positive effect on soil nitrogen, that persists after accounting for shade tree density, with these effects partly influenced by species composition, particularly the proportion of deciduous shade tree species. In contrast, no consistent effect was observed for soil potassium, and the association between richness and bulk density could not be separated from co-variation with shade tree density.

4.1 Shade tree species richness influence on soil properties.

Sensitivity analyses accounting for shade tree density confirmed that richness effects on soil nitrogen and available phosphorus were independent of tree abundance, while the bulk density finding could not be similarly verified. The following subsections discuss each soil property, with particular attention to the mechanisms underlying these patterns.

4.1.1 Soil total nitrogen

Species richness had a positive linear effect on soil total N that remained significant after accounting for shade tree density, and this relationship was significantly moderated by the proportion of deciduous shade tree species in the system. The persistence of the richness effect after shade tree density adjustment confirms that the positive association between species richness and soil N reflects a genuine diversity rather than a consequence of tree density. Indeed, shade tree density itself showed an independent negative association with soil N when richness and composition were held constant, suggesting that the two variables operate through different and partially opposing mechanisms. The deciduous moderation effect is particularly noteworthy finding: it suggests that the functional composition of shade trees, specifically the balance between deciduous and evergreen species determines not only the magnitude but also the detectability of richness effects on soil N. Where deciduous species dominate, adding species to the system produces substantially stronger N gains, whereas in predominantly evergreen systems the richness effect was weak and statistically indistinguishable from zero. The low residual heterogeneity after accounting for the deciduous proportion suggests that much of the between-study variability in N responses across the literature may be attributable to differences in shade tree trait composition rather than methodological or contextual noise.

These findings align with BEF literature reporting positive relationships between plant diversity and nitrogen cycling (Nahon et al., 2024; Nygren et al., 2012; Schwarz et al., 2021). Increased richness can enhance N through greater litter inputs, higher belowground biomass, niche complementarity in rooting depth, and stimulation of microbial activity. Systems containing deciduous or fast decomposing species tend to show stronger N responses due to higher litter quality and faster mineralization rates (Sauvadet et al., 2020).

Our findings indicate that trait composition mediates shade tree richness effects on N, with deciduous species playing a central functional role. Deciduous species typically shed leaves seasonally and produce litter with lower C:N ratios and reduced lignin content. This occurs because deciduous leaves are generally short-lived, thinner, and richer in nitrogen than the tougher, waxy leaves characteristic of many evergreen species – a difference rooted in the contrasting resource acquisition strategies of the two leaf habit types (Freschet et al., 2010; Wright et al., 2004). These litter quality differences accelerate decomposition and N mineralization, increasing the rate at which organic N is converted to plant available mineral forms (Sauvadet et al., 2020). Greater functional complementarity among deciduous species may further enhance microbial activity and nutrient turnover (Barry et al., 2019; Freschet et al., 2021; Martin and Isaac, 2015). In contrast, evergreen dominated systems with recalcitrant litter may constrain mineralization, dampening diversity effects (Sauvadet et al., 2020). The negative independent association between shade tree density and soil N observed when richness and composition are held constant may reflect increased competition for nitrogen at higher tree abundances, or shifts in nitrogen immobilization under dense systems, though this warrants further investigation. Variability across studies may therefore stem from differences in trait composition rather than shade tree species richness alone, a finding with direct implications for how shade trees are characterized and reported in future agroforestry research.

Future research should disentangle species richness effects from trait effects by incorporating quantitative litter quality traits, decomposition rates, and direct measures of N cycling processes. Long-term plot level studies are also needed to determine whether richness driven increases in soil N reflects sustained accumulation or transient increases in mineral N pools.

4.1.2 Soil organic carbon (SOC)

The relationship between species richness and SOC was best fit by a non-linear model, with increasing benefits at low to intermediate richness levels before gains plateaued. Shade tree density was not a significant predictor of SOC and the richness-density correlation was weak and non-significant, indicating that the observed quadratic richness response was not driven by co-variation with tree abundance in our dataset. This pattern is consistent with BEF theory, which predicts increasing complementarity at low to intermediate richness followed by functional redundancy or competitive saturation at higher richness levels (Cardinale et al., 2012; Tilman et al., 2014). Similar quadratic relationships have been reported in forest systems, where SOC accumulation of complementary rooting and litter niches as additional species contribute increasingly overlapping functional roles (Wang et al., 2022). In cocoa agroforestry systems, evidence is mixed. Several studies report positive association between shade tree richness and carbon stocks due to increased biomass inputs, enhanced root turnover, promotion of microbial communities, and improved soil aggregation (Abou Rajab et al., 2016; Jacobi et al., 2014; Ma et al., 2020; Prommer et al., 2020), while others document weak or neutral effects, particularly where management practices constrain organic matter inputs.

Initial SOC gains at low to intermediate richness likely reflects complementarity in litter chemistry, rooting depth distribution, and rhizodeposition, which together can promote microbial diversity and facilitate carbon stabilization through aggregation and organo-mineral associations (Cotrufo et al., 2013; Lavellee et al., 2020). A decline at higher richness was suggested by the fitted model and was supported by a subset of observations beyond the inflection point, including observations from higher-weighted studies; however, this portion of the curve should be interpreted cautiously as these observations represented a small sample size of the sample points. The apparent decline may be consistent with intensification of belowground competition or shifts in carbon allocation at higher richness levels, but given the limited data beyond the inflection point, it is not possible to rule out that it partly reflects the mathematical properties of the fitted quadratic rather than a robust ecological signal. Differences among studies likely arise from variation in stand age, baseline SOC levels, soil parent material and management intensity, including pruning and residue retention (Dawoe et al., 2014; Jacobi et al., 2014; Morales-Belpaire et al., 2024; Saputra et al., 2020).

Future research should determine whether SOC saturation reflects ecological mechanisms such as competitive suppression or biophysical limits such as mineral associated carbon stabilization capacity. Integrating soil fractionation approaches such as particulate versus mineral associated carbon would clarify stabilization pathways.

4.1.3 Soil available phosphorus

Available P increased significantly with shade tree species richness up to an intermediate level, beyond which gains plateaued. Both the positive linear and negative quadratic terms were statistically significant, confirming a non-linear relationship. Critically, shade tree density was not a significant predictor of available P, and the richness-density correlation was negligible, confirming that the observed richness effect was not attributable to tree abundance. However, the apparent decline at higher richness levels should be interpreted with considerable caution: only two data points fell beyond the inflection point, both carrying low study weights, and the descending portion of the curve therefore likely reflects the mathematical properties of the fitted quadratic rather than an empirically supported ecological trend. The robust findings here is that P availability increases with richness up to intermediate levels; conclusions about effects at higher richness remain tentative and requires a broader evidence base.

Phosphorus responses to plant diversity are widely recognised as variable and context dependent. Some studies report increased P availability in diversified systems due to complementary rooting strategies, organic acid exudation, litter traits, and enhanced microbial mediation (Hartemink, 2005; Isaac et al., 2007; Sauvadet et al., 2020), while others show inconsistent or negligible effects, reflecting strong site specific or management practices' control over P dynamics and its dependence on soil mineralogy and microbial mediation (Cuenca and Meneses, 1996; Wartenberg et al., 2017).

The observed increase at low to intermediate richness likely reflects increasing complementarity among species with differing P acquisition strategies, including variation in rooting depth and nitrogen-fixing ability, which together can stimulate rhizosphere processes and enhance P mobilisation (Isaac et al., 2007; Sauvadet et al., 2020). At low richness, limited functional diversity may constrain these mobilization mechanisms. At high richness, intensified competition for P may reduce net availability despite increased mobilization (Addo-Danso et al., 2024; Asitoakor et al., 2022). Because P dynamics are strongly influenced by soil parent material and fixation processes, richness effects may be masked in some systems that may have highly P-fixing soils.

Future studies should explicitly link species composition to P acquisition traits, including mycorrhizal association and leaf economic traits (Isaac et al., 2024; Sauvadet et al., 2020). Experimental gradients extending beyond current richness ranges would help determine whether the quadratic response reflects ecological optimization or statistical fitting.

4.1.4 Soil Potassium

In contrast to the patterns observed for total N, SOC, and available P, exchangeable K showed no statistically significant response to shade tree species richness, and the inclusion of deciduous proportion as a moderator did not resolve this. However, sensitivity analyses including shade tree density showed opposing marginal associations with soil K i.e richness negatively and density positively. This pattern is consistent with the moderate positive correlation between richness and density in the K dataset and offers a plausible explanation for the absence of a detectable richness effect in the primary analysis. That said, all estimates carried considerable residual heterogeneity and were marginal rather

than significant under REML, and this interpretation should be treated as exploratory given the small dataset.

The lack of a detectable richness effect on K likely reflects the complex and context-sensitive nature of potassium cycling, which is influenced by factors such as litter quality, weathering rates, and plant uptake dynamics that vary considerably across agroforestry systems and were not adequately captured by variables available in this synthesis. Unlike nitrogen, whose cycling is closely tied to organic matter decomposition and therefore more directly linked to litter trait composition, potassium dynamics are strongly influenced by soil mineralogy and leaching losses, making them less responsive to changes in vegetation richness *per se* (Hartemink, 2005; Tripler et al., 2006). Higher shade tree density may increase total litter inputs and K return through decomposition regardless of species composition, while increasing richness independent of total tree abundance may alter the balance of K uptake and return in ways that are not straightforwardly positive. Given the limited number of studies and substantial residual heterogeneity, conclusions about K dynamics under varying shade tree richness and density remain tentative, and future studies with larger samples and more consistent reporting of trait composition would help clarify these relationships.

4.1.5 Soil bulk density

Species richness and shade tree density were strongly and significantly correlated in the bulk density dataset, meaning that studies with higher species richness also tended to have considerably higher tree density. When both variables were included in a sensitivity model, neither richness nor density remained significant, consistent with multicollinearity rather than a genuine absence of effects. The available data therefore do not permit the independent effects of species richness and tree density on soil physical structure to be distinguished. Plant diversity and shade tree abundance are both plausibly associated with improved soil structure through increased root biomass, enhanced aggregation, and greater organic matter inputs, with diverse root architectures improving pore formation and reduce compaction, while organic inputs enhance aggregate stability (Saputra et al., 2020). However, whether it is richness, density, or their combination that drives any observed improvements cannot be determined from the current evidence base.

Variability among studies likely reflect differences in soil texture, management intensity, and stand age, which influence structural responsiveness of soil structure to vegetation change (Adiyah et al., 2022; Dawoe et al., 2014; Kutsch et al., 2009; Rasse et al., 2005). Future research should integrate bulk density measurements with considerations of both species richness and shade tree density, alongside assessments of aggregate stability, pore size distribution, and infiltration capacity, to enable the separate contributions of diversity and shade tree abundance to soil physical structure to be quantified.

Overall, the results underscore that soil responses to species richness are nutrient-specific, frequently non-linear, and mediated by trait composition – findings consistent with broader evidence from BEF research and diversified cropping systems showing that species richness alone is an insufficient predictor of ecosystem functioning (Cardinale et al., 2012; Hooper et al., 2012). Designing agroforestry

systems for improved soil functioning requires explicit consideration of trait composition, nutrient cycling pathways, and potential trade-offs among soil properties.

4.2 Evidence base and study design approaches in cocoa agroforest systems.

The publications included in this review are geographically located along the cocoa-growing regions with over 70% concentrated from South America (42%) and Africa (30%). The leading country is Ghana ($n = 9$) closely seconded by Brazil and Indonesia ($n = 8$ each), while Cote d'Ivoire, Costa Rica and Columbia each contributed four studies ($n = 4$) see Fig. 3. This distribution broadly corresponds with the global contribution in cocoa production of these countries which are all within the top 10 producers (Voora et al., 2022). While one would expect Cote d'Ivoire to have a bigger representation of publications due to the country being the largest producer of cocoa, it is suspected that most of the studies from Cote d'Ivoire could be in other languages and excluded from this review.

When these studies were analysed further, the design and choice of treatment were strongly shaped by regional patterns Fig. 3. For example, Brazilian research focuses on the rubber-cocoa systems and the cabruca systems (Araujo et al., 2018; Fontes et al., 2014; Gama-Rodrigues et al., 2010; Moço et al., 2010; Monroe et al., 2022; Nahon et al., 2024; Vicente et al., 2023). Cabruca is an agroforestry cropping system where cacao trees are grown under native trees of the Atlantic Forest of South of Bahia (Araujo et al., 2018; Gama-Rodrigues et al., 2010; Moço et al., 2010; Vicente et al., 2023). Smallholder farmers perceive these systems to have low production costs and less labour intensive (Fontes et al., 2014; Heming et al., 2022; Sambuichi et al., 2012). While West Africa research predominantly examine timber-based shade tree both at tree level and plot-level through the use of Shannon and species richness metrics (Abdulai et al., 2025; Addo-Danso et al., 2024; Andres et al., 2018; Asase and Tetteh, 2016; Asitoakor et al., 2022; Blaser-Hart et al., 2021; Borden et al., 2020; Guéi et al., 2019; Isaac et al., 2007; Koko et al., 2013; Koné and Yao, 2021; Schmidt et al., 2024; Silue et al., 2024). Other motivations for the designs are as a result of complementing farmer incomes. Specifically, the inclusion of high value shade trees of timber and fruits by farmers are usually for diversifying income streams such as timber, rubber and fruit sales and self-consumption (Anglaaere et al., 2011; Heming et al., 2022; Ramírez et al., 2001; Ramírez-Argueta et al., 2022).

4.3 Mechanisms and factors influencing the observed effects.

Our meta-analysis identifies several factors associated with the effects of species richness on soil nutrient status and cocoa yield responses, including shade tree density, Species trait composition, cocoa age and farm management. However, while statistical associations were detected in our meta-analysis, the mechanisms underlying these patterns are inferred from both the qualitative included publications and the broader literature rather than directly tested.

Firstly, the results indicate that shade tree species richness alone does not adequately explain the variation in soil nutrient properties. An incorporation of deciduous species composition variables into our meta-analytic models resulted in clear patterns for some soil properties. For example, we found that a higher deciduous shade tree proportion positively modifies the effects of shade tree species richness on soil total nitrogen (*Table S 5*). This pattern is consistent with the findings of (Sauvadet et al., 2020), who noted a positive association with deciduous species on soil N and p availability due to their high litter quality. While our meta-analysis does not directly quantify and link litter inputs or decomposition rates, the observed association is compatible with a litter-mediated nutrient cycling pathway.

In contrast, although nitrogen fixing shade trees are commonly expected to increase soil nitrogen availability (Sauvadet et al., 2020), we did not detect a significant effect of higher nitrogen-fixer proportion in a plot on soil total nitrogen. This absence of effect likely reflects limited and uneven representation of nitrogen-fixing species across studies, reducing statistical power for trait-level meta-analytic comparisons. It should therefore not be interpreted as evidence against trait-based nutrient inputs, but rather as a limitation of the available dataset.

Temporal dynamics and farm management practices such as pruning, thinning and historical land use also appear to shape soil nutrient responses. Soil Organic Carbon (SOC) is reported and believed to be context-dependent linked to its slow accumulation and sensitivity to past management, making long term observations essential to understanding its dynamics. For example, a study in Ghana by (Dawoe et al., 2014) reported an initial decline in SOC following forest conversion to cocoa plantation, and starts to improve 15 years after establishment. Other studies have shown that the use of shade trees in cacao plantations promotes a continuous deposition of plant residues which may contribute to the maintenance of high soil organic matter (Moço et al., 2010; Oelbermann et al., 2006; Smiley and Kroschel, 2008). Increased organic matter is in turn associated with changes in soil physical, chemical and biological properties (Huerta et al., 2007; Isaac et al., 2007; Moço et al., 2010; Norgrove et al., 2009). These linkages, however, are drawn from individual field studies rather than directly demonstrated within our meta-analysis.

Finally, residual heterogeneity remained in some soil properties analysis models i.e soil Potassium (K), suggesting that unmeasured site-level variables such as soil type, baseline fertility, rainfall regime, and management intensity contribute to the variations in outcomes. Regional biogeography and edaphic contexts likely influence both the baseline soil nutrient status and the potential magnitude of response to agroforestry interventions.

5 Review limitations

This systematic review is subject to both limitations in the available evidence base and constraints associated with the review process.

A primary limitation is the small number of studies eligible for quantitative synthesis, which restricted the statistical power of the meta-analysis and limits the robustness and generalisability of the findings.

Many studies were excluded because they did not include cocoa monoculture as comparator or baseline, lacked sufficient variation in species richness (e.g fewer than three richness levels). As a result, the evidence base is uneven and may not fully represent the richness of cocoa agroforestry systems globally.

There were also important gaps in reported outcomes, particularly for variables such as cocoa yield and litter decomposition dynamics. This constrained our ability to evaluate trade-offs between productivity and soil nutrient cycling processes and limited the potential for causal or pathway-based analysis linking shade tree richness, ecosystem functioning and productivity outcomes.

Finally, this review was limited to English-language publications, which may have resulted in the omission of relevant studies.

Taken together, these limitations constrain the confidence that can be placed in the magnitude and generality of the reported effects. While consistent patterns emerge for some soil properties, particularly soil total nitrogen and soil organic carbon, the overall strength of evidence remain moderate and more limited for trait-based mechanisms and underreported outcomes.

6 Conclusions

Implications for policy and practice

This review finds that increasing shade tree species richness in cocoa agroforestry systems is generally associated with positive effects on some soil nutrient properties, particularly soil total nitrogen, soil organic carbon, and available phosphorus. However, these effects are not consistent across all nutrients or systems, and no clear effect was detected for exchangeable potassium.

The available evidence indicate that outcomes depend on context, including species functional trait composition, and management conditions. There is some indication that systems with functionally distinct species, such as deciduous shade trees, may provide greater benefits for certain soil properties.

Overall, the evidence supports the potential for shade tree richness to contribute to soil fertility in cocoa systems, but it does not provide a sufficient basis for specific recommendations on optimal richness levels or species combinations. The strength of evidence is moderate and uneven across outcomes, which limits the extent to which findings can be generalized across regions and management contexts.

Implications for Research

The evidence base is limited by small number of studies, inconsistent reporting of key variables, and uneven coverage of functional traits and soil outcomes. In particular, there is a lack of studies that directly link shade tree leaf phenology traits to soil nutrient dynamics, as well as limited data on outcomes such as cocoa yield and litter decomposition, which are important for understanding trade-offs and underlying mechanisms.

Future research should prioritize: (i) the use of standardized and clearly reported measures of species traits and soil properties; (ii) study designs that include appropriate comparators and gradient of species richness; and (iii) longer-term or experimental approaches that enable clearer attribution of causal mechanisms, including nutrient cycling processes (e.g litterfall and decomposition rates).

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The R code and datasets analysed during the current study are included in the supplementary and available here <https://doi.org/10.5281/zenodo.21638128>.

Competing interests

The authors declare that they have no competing interests that might be perceived to influence the results and/or discussion reported in this paper.

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Authors' contributions

LL: Conceptualization; Data curation; Formal analysis; Investigation; methodology; Visualization; Writing – original draft; Writing – review and editing. MR Investigation; Validation; Writing – review and editing. JA: Interpretation; Writing – review and editing. ED: Interpretation; Writing – review and editing. DH Formal analysis; Methodology; Writing – review and editing. JAG: Methodology; Supervision; Writing – review and editing. NS Conceptualisation; Supervision; Writing – review and editing. WT Conceptualisation; Methodology; Supervision; Funding ; Writing – review and editing.

All authors approved the submitted version and agreed to be personally accountable for their own contributions and for the accuracy and integrity of the work as a whole.

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Figures

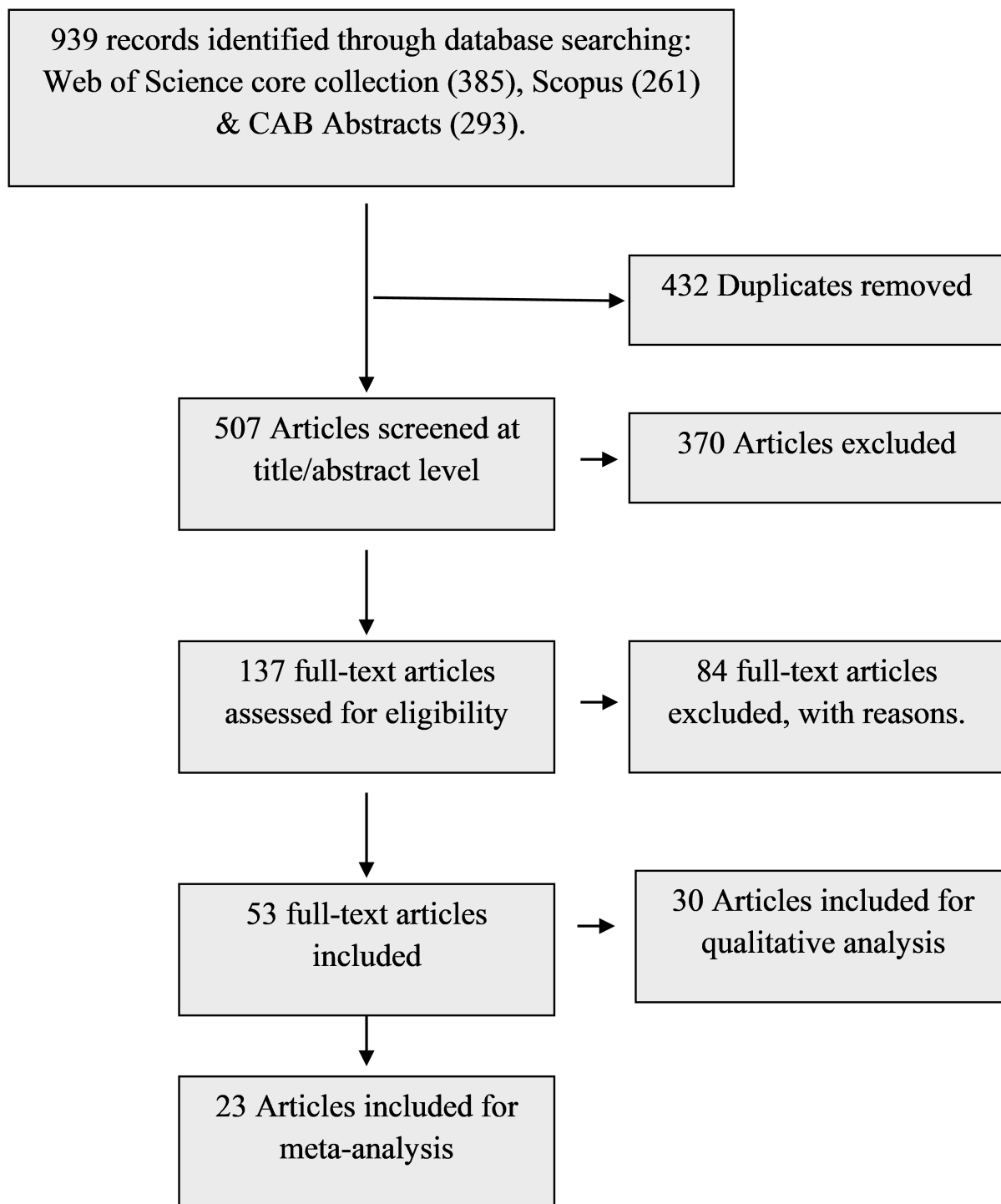


Figure 1

ROSES flow diagram showing the different stages of the review and screening process that led to the inclusion of 53 Articles for this synthesis.

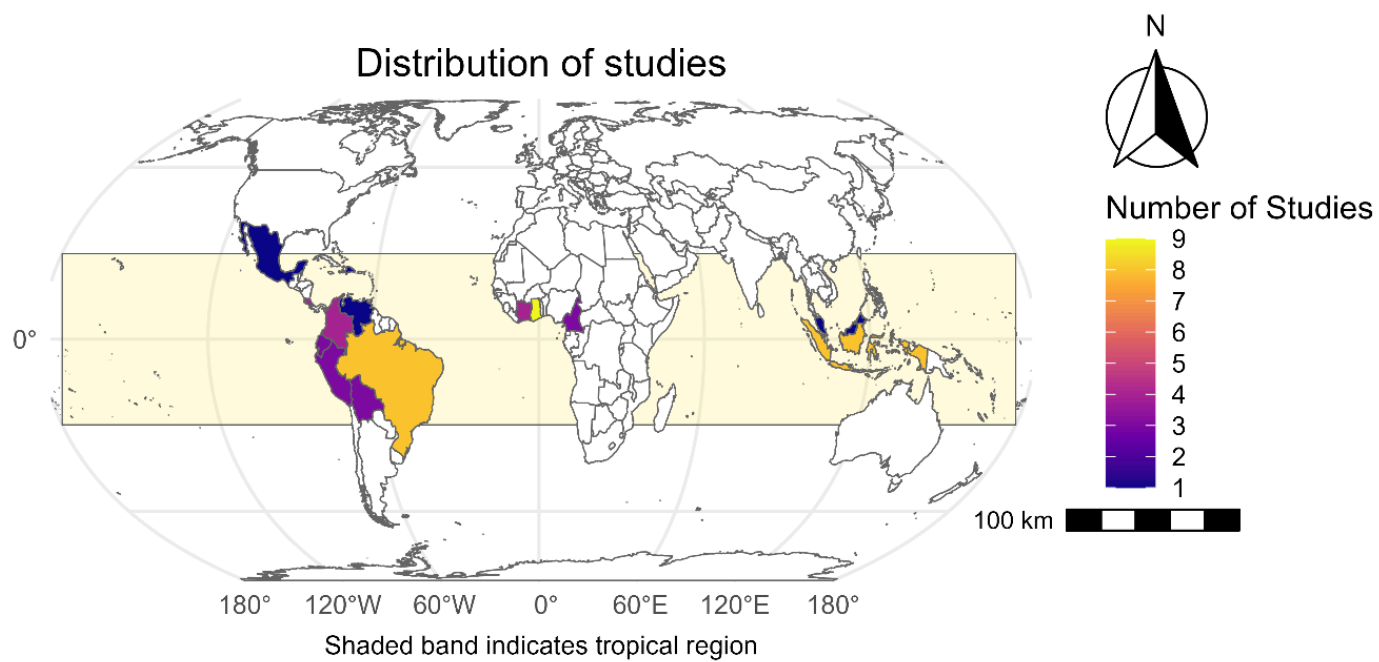


Figure 2

Global distribution of included studies

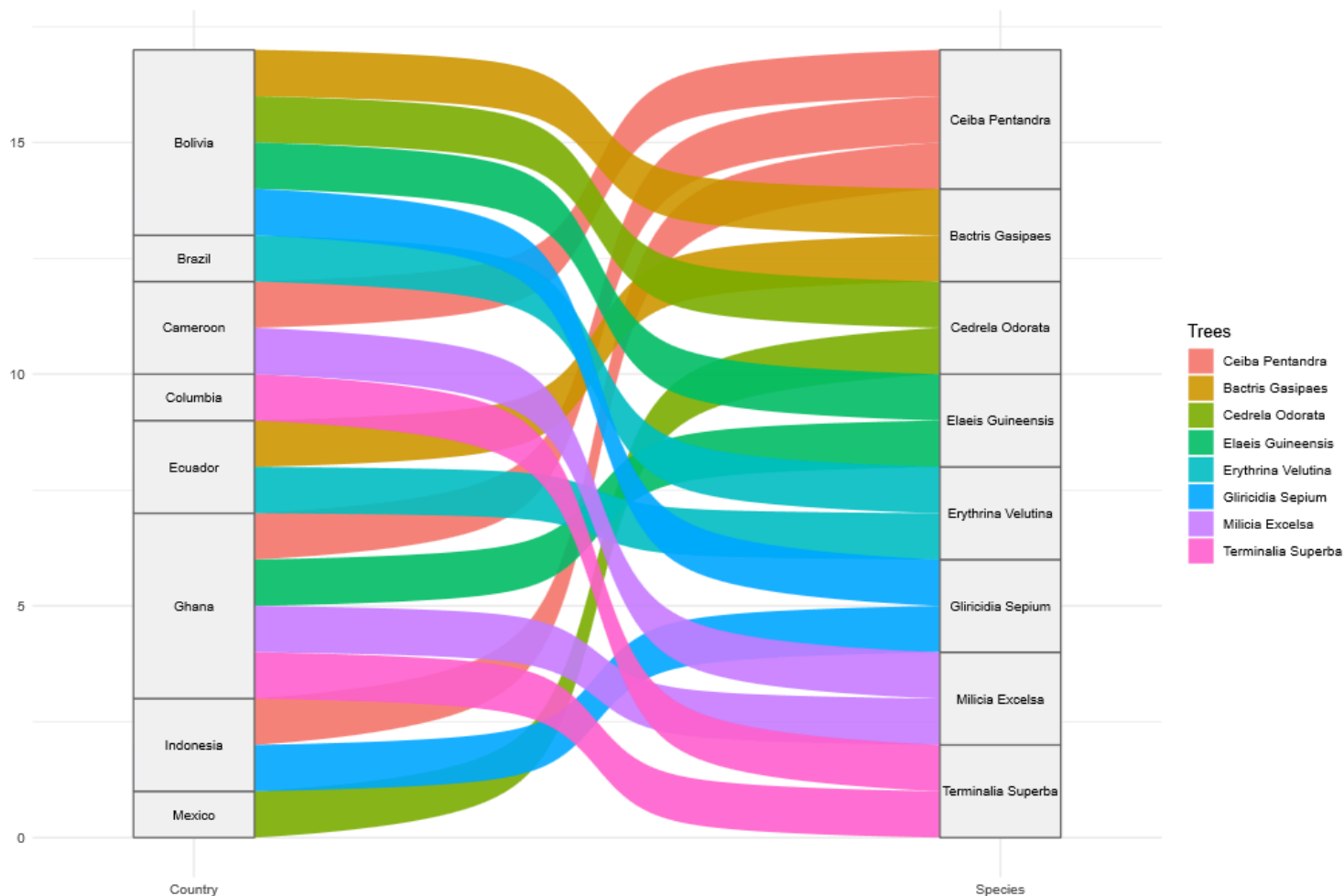


Figure 3

Shade tree species reported across cocoa agroforestry studies included in the meta-analysis, by country of origin. The Sankey diagram illustrates the distribution of the top 8 most reported shade tree species across eight countries. Each flow connects a country to the shade tree species recorded within studies from the location. Species appearing in more than one country are represented by a shared colour.

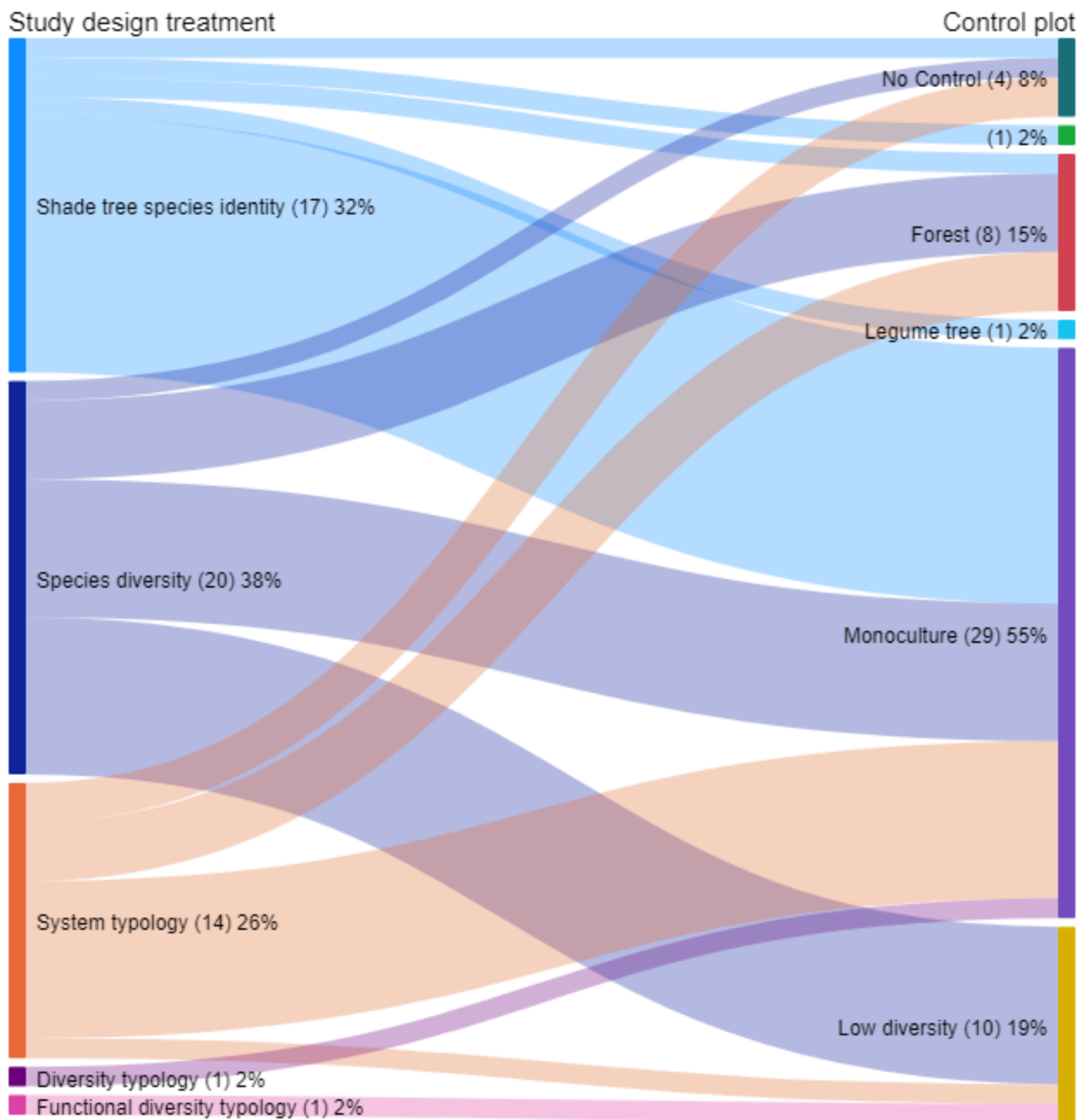


Figure 4

Figure 3: Experimental designs and control treatments used across included studies, studies are grouped by treatment approach. The most common experiment design is the species diversity (38%) followed by shade tree species identity and monoculture (55%) as the most used control followed by low diversity (19%) and forest plots (25%).

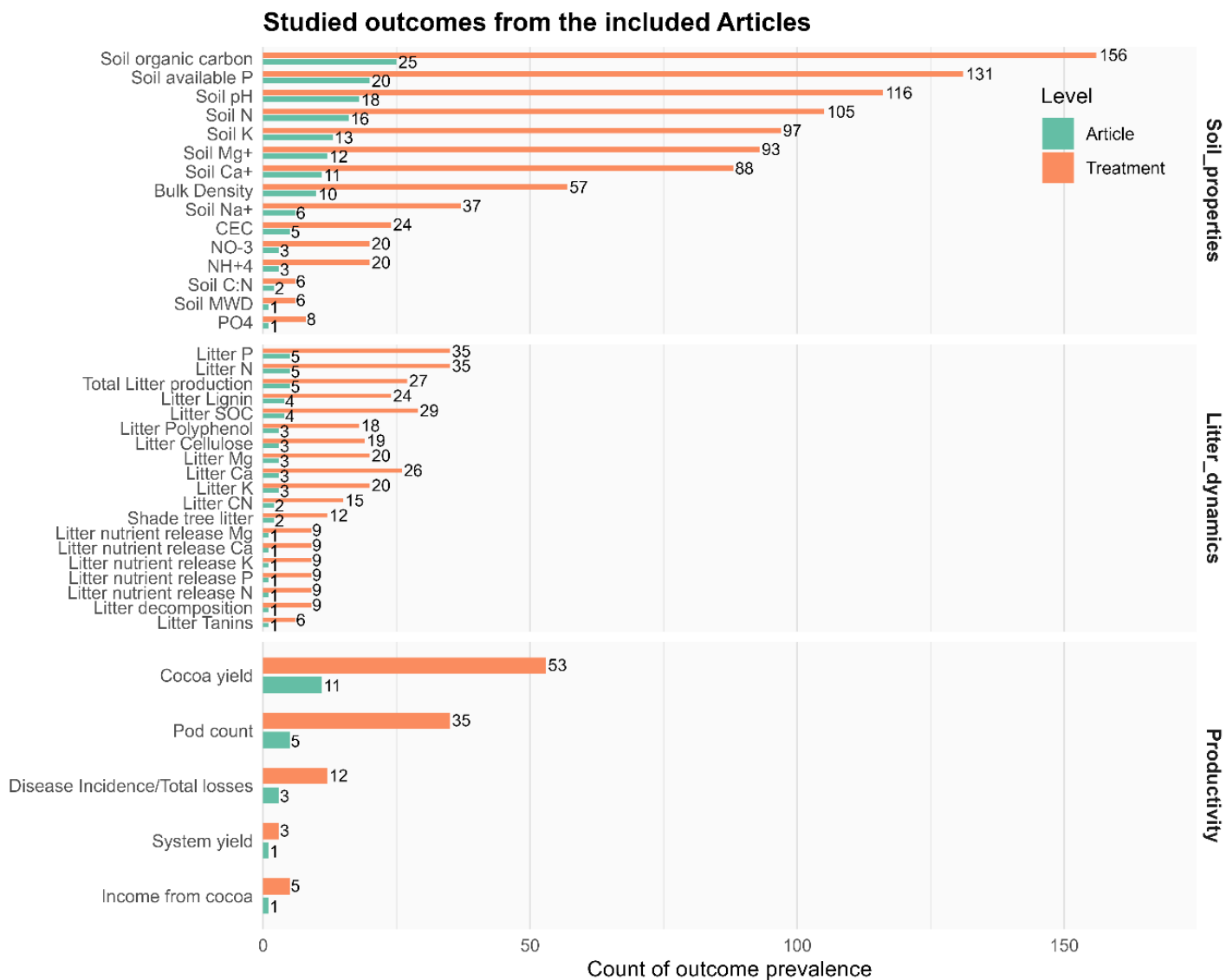


Figure 5

Figure 4: Share of outcomes assessed in the included studies. The most reported outcomes were the soil properties for example SOC reported in 25 studies and cocoa yield reported in 11 studies. The least reported outcomes were litter-dynamics.

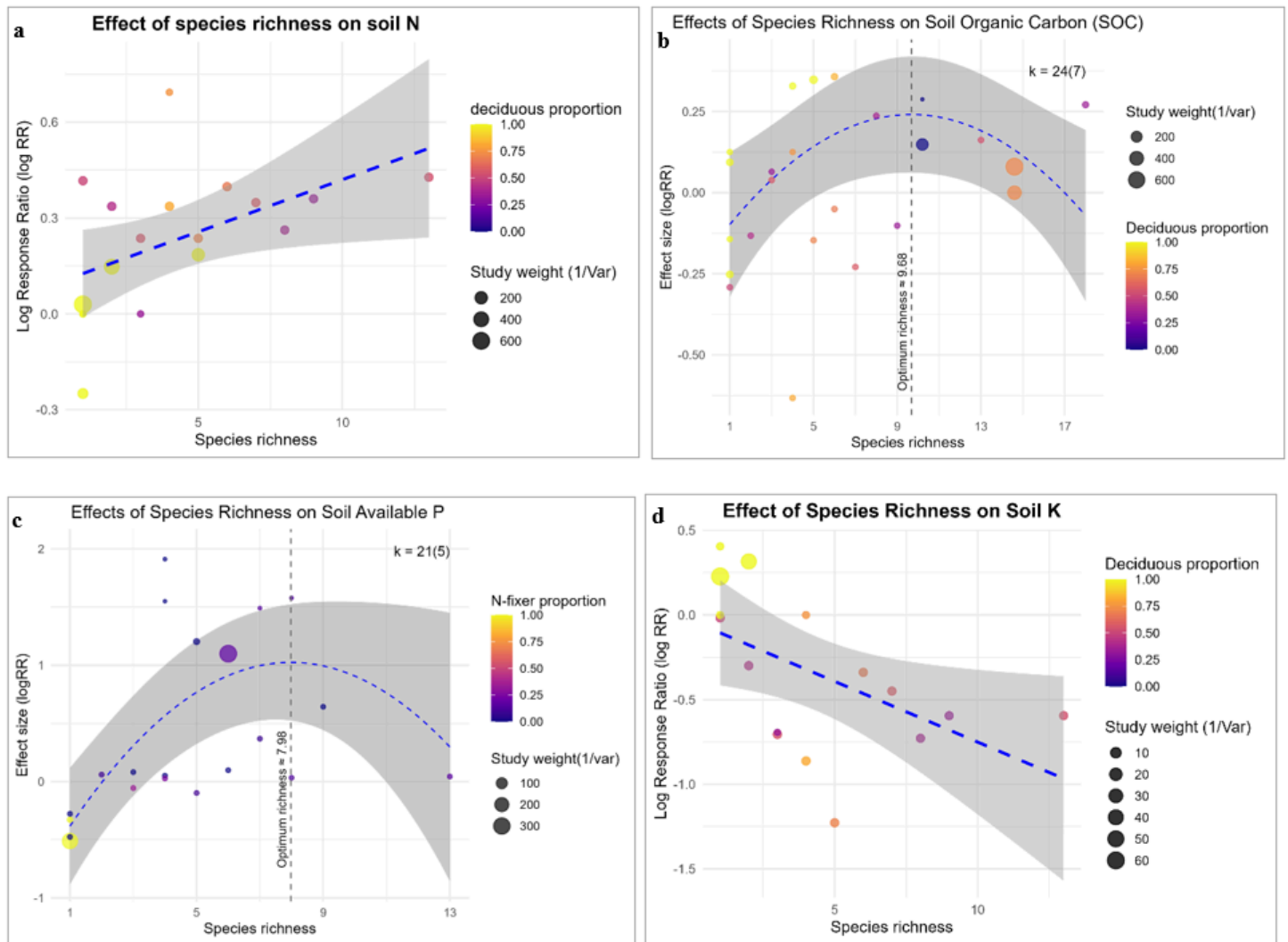


Figure 6

Figure 6: Meta-analysis multilevel results showing the effects of shade tree richness on soil biochemical properties (a) effects of species richness and nitrogen fixing proportion on soil Nitrogen, (b) effects of species richness and nitrogen fixing proportion on soil organ carbon (SOC), (c) effects of species richness on soil available Phosphorus (P), and (d) effects of species richness and deciduous tree proportion on soil Potassium.

Effect of Species Richness on Soil Bulk Density (BD)

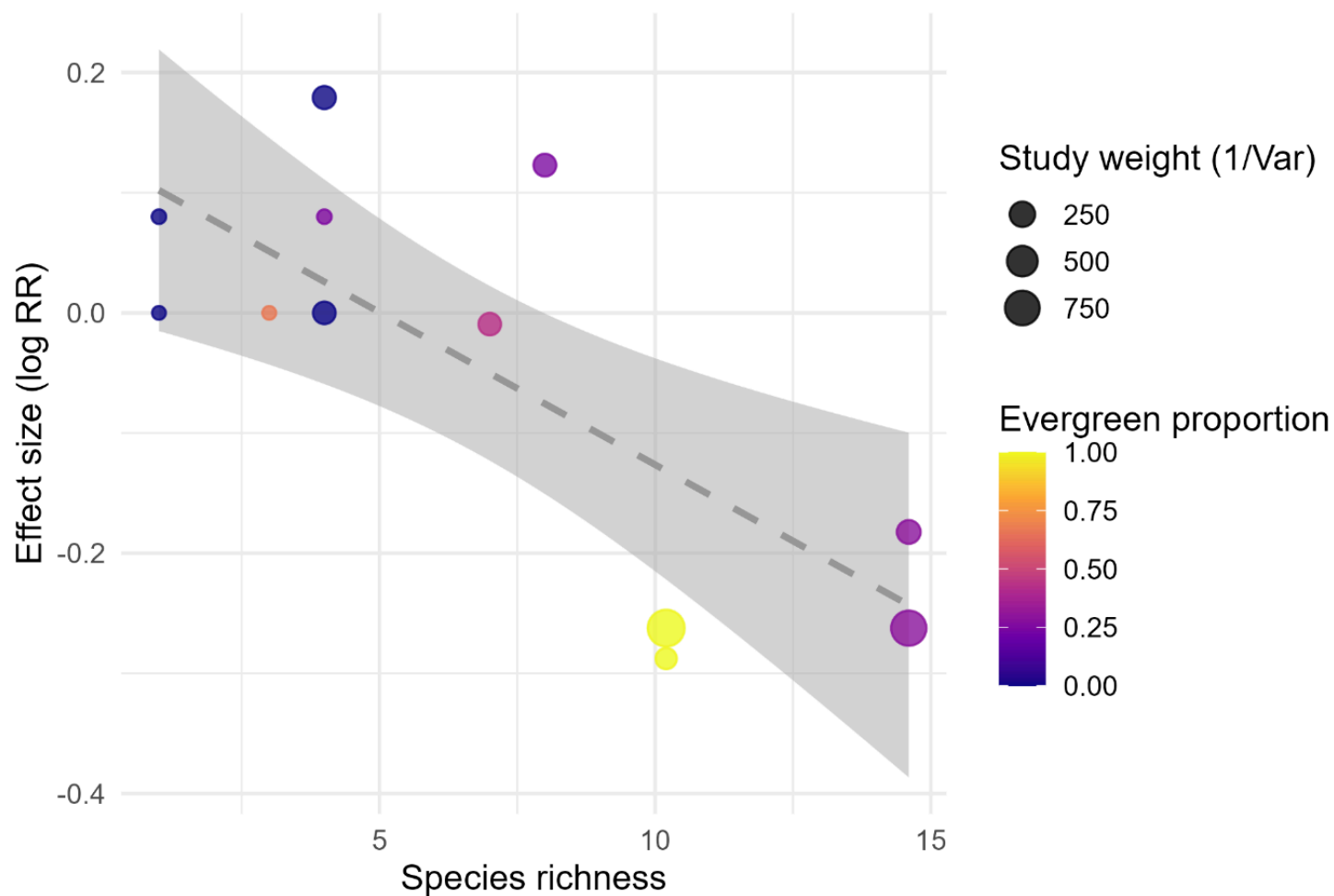


Figure 7

Figure 7: Effects of shad tree species richness on soil bulk density and the influence of evergreen proportion.

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