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Cocoa Agroforestry in a Warming World: A Critical Synthesis of Shade Design, Carbon, Biodiversity, Yield and Climate Resilience

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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Abstract

Cocoa production is increasingly exposed to heat, rainfall variability and severe drought, while the ecological simplification of many cocoa landscapes has reduced the biological and structural buffers that can moderate climatic stress. Cocoa agroforestry is therefore promoted as a strategy that can simultaneously support adaptation, carbon storage, biodiversity and farmer livelihoods. Yet this proposition is often expressed too generally: shade can cool cocoa canopies and reduce atmospheric demand, but shade trees also compete for light and water, alter pest and disease environments, and create labour and economic obligations. This critical narrative review evaluates how shade-tree identity, functional traits, canopy architecture, density and spatial arrangement mediate these trade-offs. Literature published from 1 January 2000 to 15 July 2026 was considered, with earlier or later records excluded from the evidential synthesis except where bibliographic verification was required. Evidence was appraised for design quality, climatic context, duration, measurement validity and transferability across producing regions. The synthesis shows that cocoa agroforestry cannot be reduced to a universal shade percentage. Elevated crowns, seasonally appropriate leaf phenology, complementary rooting and useful by-products can improve microclimate regulation while limiting crop competition, whereas poorly matched species or excessive canopy closure may depress yield, intensify water competition or favour disease. Aboveground

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carbon gains under agroforestry are well supported, but soil-carbon responses are less consistent and forest conservation remains irreplaceable. Biodiversity generally benefits from structural complexity relative to open cocoa, although agroforests remain imperfect substitutes for intact forest and responses depend on land-use history and landscape context. Economic evidence further shows that yield alone is an inadequate indicator of farm performance. The most defensible pathway is climate-contingent functional shade design combined with farmer knowledge, monitoring and adaptive management. Future research should prioritise long-term, multi-site experiments that jointly quantify crop physiology, yield, biodiversity, carbon, disease, labour and profitability under realistic climate extremes.

Keywords: *Climate adaptation; climate mitigation; Theobroma cacao; functional traits; ecosystem services; drought; shade-tree management.*

1. Introduction

Cocoa, produced from *Theobroma cacao* L., is a perennial tropical crop whose productivity depends on interactions among climate, soils, plant genetics, farm management and surrounding landscape structure. The crop evolved as an understorey tree and can be cultivated beneath retained forest trees or planted shade canopies, but commercial production now spans a continuum from complex, multi-strata agroforests to nearly unshaded monocultures. This management gradient is not merely an aesthetic or conservation distinction. It changes radiation, air and leaf temperature, vapour pressure deficit (VPD), soil-water dynamics, nutrient cycling, pest and pathogen environments, habitat availability, biomass carbon, labour requirements and the portfolio of products available to farm households (Tscharntke *et al.*, 2011; Vaast & Somarriba, 2014). Consequently, the choice of shade regime has become central to debates about the future of cocoa under climate change. Recent evidence from young cocoa stands further indicates that stand structure and cocoa crown development interact to shape early growth and yield, supporting the evaluation of agroforestry as a spatially designed system rather than as shade presence alone (Ariza-Salamanca *et al.*, 2024).

Climate exposure is already a material constraint in several major cocoa regions. Suitability modelling for Ghana and Côte d'Ivoire projected spatially heterogeneous losses in future climatic suitability, with dry-season temperature and moisture constraints emerging as important limits rather than a uniform contraction of the entire cocoa belt (Läderach *et al.*, 2013; Schroth *et al.*, 2016). This spatial heterogeneity matters for management because a practice that is useful in a warm but adequately watered location may fail at a drought-prone forest-savanna margin. Regional adaptation analyses consequently argue for differentiated strategies rather than uniform prescriptions, including intensification in relatively stable zones, agronomic adjustment and diversification in moderately exposed zones, and eventual crop transition where climatic suitability becomes severely constrained (Schroth *et al.*, 2017).

Shade is frequently proposed as the farm-level bridge between those regional risks and cocoa physiology. Trees can intercept solar radiation, reduce daytime temperature and VPD, shelter cocoa leaves from extreme radiative loading, add litter, and provide physical and biological habitat complexity. At the same time, shade trees transpire water, occupy rooting space, capture nutrients and reduce photosynthetically active radiation reaching cocoa. The balance between facilitation and competition therefore shifts with rainfall, soil depth, shade-tree species, root architecture, canopy position, season, cocoa age and management intensity. A Ghana field study during exceptionally dry conditions illustrates the danger of treating shade as intrinsically protective: cocoa under two shade-tree species suffered greater hydraulic stress and mortality than cocoa in full sun, apparently because tree-crop competition intensified when soil water became critically scarce (Abdulai, Vaast, *et al.*, 2018). Conversely, a 33-month rain-suppression experiment in Ghana found that uniform 40% shade increased soil moisture and improved cocoa physiological performance, growth and yield relative to full sun, even though it did not eliminate the negative effects of reduced rainfall (Mensah *et al.*, 2023). These results are not mutually exclusive; they demonstrate that shade effects are conditional on tree traits, hydrological context and drought severity.

The same conditionality characterises production, carbon and biodiversity outcomes. A multi-dimensional meta-analysis found that cocoa agroforestry tends to store more carbon and support environmental functions than monoculture, while mean cocoa yield is often lower and economic outcomes are much more variable than a simple yield comparison suggests (Niether *et al.*, 2020). Long-term and plot-scale studies also show that substantial carbon storage can coexist with commercially relevant cocoa yields, but the strength of that compatibility differs with stand structure and site (Abou Rajab *et al.*, 2016; Somarriba *et al.*, 2013). Biodiversity evidence is similarly asymmetric: structurally complex agroforests usually retain more biodiversity than open agricultural systems, yet they do not reproduce the composition or intactness of primary forest, and their conservation value depends strongly on how the agroforest was established and on the amount of natural habitat remaining in the landscape (De Beenhouwer *et al.*, 2013; Maney *et al.*, 2022; Schroth & Harvey, 2007). Land-use history can also shape the taxonomic and functional diversity of shade-tree communities, indicating that conservation outcomes depend on both present stand structure and the pathway through which cocoa agroforests were established and managed (Maza-Villalobos *et al.*, 2024).

A second shift in the literature is conceptual. Early recommendations commonly described shade through canopy cover or tree density. More recent research treats the shade layer as a set of functional traits that can be designed. Crown base height changes competition for light; leaf phenology changes the seasonality of shade; leaf chemistry and litter quality influence nutrient turnover; rooting depth influences competition for water; and tree stature and wood density influence carbon storage and wind risk (Isaac *et al.*, 2024). In Ghana, elevated-canopy shade trees buffered temperature and VPD while avoiding the yield penalties associated with low crowns and storing more carbon (Blaser-Hart *et al.*, 2021). More recent work grouped shade trees by leaf phenology and found that fully deciduous phenological strategies produced particularly favourable combinations of microclimate, soil water, cocoa physiology and yield in a northern Ghana setting (Abdulai *et al.*, 2025). The emerging management question is therefore not simply how much shade cocoa requires, but which trees should provide shade, where their crowns and roots should be positioned, how their phenology should align with seasonal stress, and how the system should be pruned and renewed over time. Farm-network evidence additionally links community-level shade-tree traits with soil- and cocoa-related ecosystem services, reinforcing the value of trait-based management while showing that responses remain contingent on agroecological and soil context (Addo-Danso *et al.*, 2024).

Existing reviews have established important foundations. Broad agroforestry syntheses have described multifunctional shade management and biodiversity benefits (De Beenhouwer *et al.*, 2013; Tscharntke *et al.*, 2011), cocoa-specific meta-analysis has compared agroforestry with monoculture across agronomic, ecological and socioeconomic dimensions (Niether *et al.*, 2020), and recent trait-based work has reviewed which shade-tree attributes influence agroecosystem functions across coffee and cocoa systems (Isaac *et al.*, 2024). What remains less well integrated is the climate-contingent interaction among physiological adaptation, carbon mitigation, biodiversity conservation, yield stability and farm economics, especially in light of field evidence published during 2020-2026. That newer evidence challenges both unqualified promotion of shade and yield-centred arguments for simplification. It supports a more discriminating framework in which agroforestry performance depends on functional design and on whether farmers have the labour, tenure security, planting material, markets and extension support needed to manage that design. Recent farmer-based evidence from Nigeria likewise shows that shade trees are valued for multiple livelihood and climate-regulation functions, supporting the inclusion of local priorities alongside ecological criteria in shade-management design (Brown *et al.*, 2025).

1.1 Scope, Research Gap and Objectives

This review examines cocoa agroforestry as a managed socioecological system under climatic warming, with particular emphasis on shade-tree design and its consequences for microclimate, water relations, yield, carbon storage, biodiversity, pest and disease regulation, profitability and resilience. The central research gap is the absence of a sufficiently integrated framework that distinguishes the effects of shade quantity from the effects of shade-tree identity, architecture, phenology and spatial arrangement while also accounting for climatic exposure and farmer economics. The review therefore evaluates where current evidence supports broadly transferable principles, where findings remain site-specific or contradictory, and how those uncertainties should change management recommendations. The principal objectives are to synthesise the physiological basis of shade responses, critically evaluate trade-offs among production and ecosystem services, identify the design variables most likely to reconcile competing objectives, and define research and implementation priorities for climate-resilient cocoa landscapes. The review does not treat agroforestry as a substitute for intact forest conservation, does not attempt a formal meta-analysis, and does not prescribe a single universal canopy-cover target.

2. Methods for Literature Selection

2.1 Review Design and Rationale

A critical narrative review design was selected because the topic spans heterogeneous evidence types that cannot be combined meaningfully through a single quantitative effect model. Relevant studies include climate-suitability modelling, field manipulations of rainfall and shade, farm surveys, long-term system comparisons, biodiversity modelling, carbon inventories, pest-exclusion experiments, economic analyses and qualitative adoption studies. The purpose was therefore to evaluate mechanisms, reconcile conflicting findings and assess transferability across contexts rather than estimate one pooled effect size. The review nevertheless used an explicit search strategy, stated eligibility criteria and structured evidence appraisal because narrative synthesis still requires transparent source selection and critical reasoning. The quality principles described by Baethge *et al.* (2019) informed the approach, particularly the need to justify relevance, describe literature searching, cite claims appropriately and present scientific reasoning rather than opinion.

2.2 Information Sources

Literature discovery used AGRIS, OpenAlex, DOAJ, PubMed, Semantic Scholar, Google Scholar, SciELO and African Journals Online (AJOL). Searches were supplemented by backward and forward citation tracing from high-quality reviews and pivotal empirical papers, related-article searching, and targeted checks of authoritative institutional and article landing pages. DOI and bibliographic metadata were cross-checked against DOI landing pages, PubMed records where applicable, official journal article records and scholarly repositories that reproduced the publication metadata. Searches for corrections, retractions or conflicting bibliographic records were also undertaken before references were retained.

2.3 Search Strategy and Search Period

The principal eligible publication period was 1 January 2000 to 15 July 2026. Searches were executed on 13 September 2026 while applying 15 July 2026 as the bibliographic cut-off for evidence inclusion. The year 2000 was selected to capture the modern literature on cocoa agroforestry multifunctionality, ecosystem services and climate adaptation while allowing older foundational evidence to be considered if indispensable. In practice, the final evidential set was dominated by studies published after 2007. Search concepts combined cocoa terms with agroforestry structure, climate exposure, crop performance, carbon, biodiversity, functional traits and socioeconomic implementation. Representative query blocks and their intended evidence domains are summarised in Table 1. Boolean syntax was adapted to the capabilities of each source without changing the underlying concepts.

Table 1 is intended to make the discovery logic reproducible rather than imply a systematic-review record count. Each query block was used iteratively and combined with citation tracing; inclusion still depended on the eligibility and appraisal criteria described below.

Table 1. Representative search-query blocks and evidence domains

Query block	Representative Boolean terms	Primary evidence domain
Core cocoa agroforestry	(cocoa OR cacao OR "Theobroma cacao") AND (agroforestry OR shade OR "shade tree")	System definitions, management gradients and general agroforestry evidence
Climate exposure and microclimate	core AND ("climate change" OR warming OR drought OR heat OR "vapour pressure deficit" OR rainfall OR microclimate)	Climate suitability, temperature buffering, drought response and water relations
Production and resources	core AND (yield OR productivity OR "soil moisture" OR physiology OR nutrients OR competition)	Yield, crop physiology, light, water and nutrient interactions
Carbon and mitigation	core AND (carbon OR biomass OR "soil organic carbon" OR sequestration OR "greenhouse gas" OR mitigation)	Aboveground carbon, soil carbon and greenhouse-gas balance
Biodiversity and ecological function	core AND (biodiversity OR "species richness" OR birds OR bats OR ants OR "biological control")	Conservation value, community intactness and ecological regulation
Shade-tree functional traits	core AND ("functional trait" OR "canopy height" OR phenology OR crown OR rooting OR deciduous)	Tree architecture, phenology, rooting and litter traits
Economics and adoption	core AND (profit OR profitability OR income OR cost OR costs OR labour OR adoption OR tenure OR livelihood OR livelihoods OR market OR markets)	Farm economics, adoption constraints, tenure and livelihood outcomes
Integrated resilience	core AND ("trade-off" OR "trade-offs" OR multifunctionality OR resilience OR adaptation OR landscape)	Cross-domain trade-offs, resilience and landscape planning

Note. "core" denotes the cocoa-agroforestry concept block shown in the first row. Database-specific syntax was adjusted without altering the underlying concepts

2.4 Eligibility Criteria

Eligible sources were peer-reviewed journal articles and methodologically relevant reviews directly addressing cocoa agroforestry, cocoa climate vulnerability, shade-tree functions, cocoa production under contrasting shade, carbon storage, biodiversity, pest or disease regulation, farmer economics, or adoption and governance. Multi-crop agroforestry reviews were retained only when cocoa evidence was explicit and analytically relevant. Studies from all cocoa-producing regions were eligible because the review aimed to distinguish general mechanisms from geographically contingent outcomes. English-language articles predominated; non-English records could be considered when bibliographic metadata and substantive findings were sufficiently accessible for verification. Studies outside the main period were eligible only when conceptually foundational, although no pre-2000 study was necessary in the final synthesis.

Exclusion criteria were non-scholarly promotional material, unverifiable articles, records with incomplete or conflicting bibliographic identity, studies with no material connection to cocoa or agroforestry, and sources published after 15 July 2026. Preprints were not used where peer-reviewed evidence was available. Articles focused solely on molecular breeding, fermentation, chocolate processing or post-harvest quality were outside scope unless they directly addressed farm-level climate resilience. Forest-conservation evidence was used to establish landscape baselines, but comparisons that implicitly equated agroforest carbon or biodiversity with intact forest were treated cautiously.

2.5 Screening, Duplicate Handling and Study Selection

Titles and abstracts were first assessed for direct relevance to the review objectives. Full texts or sufficiently detailed scholarly records were then examined to confirm study context, design, outcome definitions and the relationship between reported findings and the claims for which they might be cited. Duplicate records identified through title, DOI and author-year matching were consolidated. Where the same article was indexed by multiple services, the most authoritative and complete bibliographic record was retained for metadata checking. No screening counts are reported because this was a critical narrative review rather than a systematic review with an auditable record-by-record flow. Inaccessible or unverifiable papers were not used as evidential support.

2.6 Critical Appraisal and Evidence Synthesis

Evidence was appraised according to design appropriateness, duration, replication, spatial representativeness, measurement quality, treatment of climatic context and confounding, and relevance to real farm management. Greater interpretive weight was given to long-term experiments, well-replicated manipulations, multi-site farm studies and syntheses with explicit comparison groups. Cross-sectional associations were used to identify patterns but were not interpreted as proof of causation. For climate-resilience claims, particular attention was paid to whether studies measured actual drought or heat exposure rather than inferring resilience from shade presence alone. For carbon, biomass and soil pools were distinguished; for biodiversity, species richness was separated from community intactness and landscape history; and for economics, gross yield was distinguished from costs, net income and diversified products. Conflicting results were organised around plausible moderators including climate zone, shade-tree species, crown architecture, leaf phenology, rooting interactions, soil conditions, cocoa genotype, input intensity and farm scale.

3. Climate Exposure and the Physiological Basis of Shade Responses

Cocoa sensitivity to climate is governed not by annual rainfall alone but by the timing of water deficits, atmospheric demand, temperature extremes and the capacity of soil and roots to sustain transpiration. Climate-suitability models for West Africa illustrate this distinction. Läderach *et al.* (2013) projected that future suitability changes in Ghana and Côte d'Ivoire would be spatially heterogeneous, while Schroth *et al.* (2016) identified rising maximum temperatures during the dry season as an increasingly important constraint. These modelling studies are valuable for locating broad risk gradients, but they operate at spatial scales much coarser than the farm processes through which shade actually influences cocoa. Their principal management implication is therefore not that shade will rescue all threatened cocoa, but that different climatic zones will require different responses and, in severely deteriorating environments, agronomic adaptation may eventually be insufficient (Schroth *et al.*, 2017).

Field evidence clarifies the underlying physiology. Mature cocoa has a relatively shallow rooting profile in some soils, which can make production sensitive to prolonged reductions in throughfall. In a 13-month throughfall-displacement experiment in Sulawesi, Moser *et al.* (2010) found most fine and coarse root biomass in the upper 40 cm and documented substantial physiological adjustment to imposed drought. The associated *Gliricidia sepium* shade trees differed in their vertical rooting distribution, illustrating that root complementarity can reduce direct competition where species combinations are favourable. Such complementarity cannot be presumed for all shade species, because rooting depth, fine-root proliferation and hydraulic strategy differ markedly among trees.

The most important empirical contradiction in the cocoa shade literature concerns whether shade buffers or magnifies drought. Abdulai, Vaast, *et al.* (2018) compared full-sun cocoa with cocoa beneath *Albizia ferruginea* and *Antiaris toxicaria* in Ghana across wet, dry and extremely dry conditions. During the extreme drought, cocoa mortality was severe beneath both shade species, whereas full-sun cocoa maintained better access to soil water. The result is a strong warning against inferring drought resilience from cooler understorey temperature alone. A tree that reduces radiation can simultaneously deplete shared soil water through transpiration. Under mild atmospheric stress, cooling may dominate; under extreme edaphic drought, below-ground competition can become decisive.

Mensah *et al.* (2023) reached a different but compatible conclusion in a 33-month split-plot manipulation of rainfall and shade in Ghana. Uniform 40% shade increased volumetric soil moisture and improved cocoa physiological performance, growth and dry-bean yield relative to full sun. Yet the interaction between shade and rainfall suppression did not show that shade cancelled drought damage. Shade improved the baseline growing environment, while progressively stronger rain exclusion still reduced performance. The distinction is important for extension: a beneficial mean shade effect is not equivalent to insurance against a severe rainfall failure.

Observations from real climatic extremes reinforce the need to treat resilience as survival and recovery, not simply mean yield. During the 2015-2016 El Niño-associated drought in Bahia, Brazil, Gateau-Rey *et al.* (2018) recorded substantial losses in cocoa agroforests and linked the event to pronounced mortality and production decline. Such evidence demonstrates that complex agroforests remain vulnerable to drought of sufficient magnitude. Resilience therefore has at least three separable dimensions: buffering of microclimate during ordinary heat, maintenance of water status during seasonal dry periods, and avoidance of mortality or prolonged yield collapse during extremes. A shade regime may perform well on the first dimension yet poorly on the third.

Farm surveys along climatic gradients add a production perspective. Abdulai, Jassogne, *et al.* (2018) found much lower mean cocoa yield in a dry Ghanaian region than in mid and wet regions, greater use of medium shade in the dry region, and no consistent yield advantage of low shade outside the wet region. In the wet region, lower shade was associated with higher yield. These data are observational and cannot isolate shade from soils, farm age, inputs or farmer selection, but they support the biological expectation that the yield cost and protective value of shade vary with climate. They also show why national shade recommendations are unlikely to be optimal when applied without agroecological zoning.

Microclimate itself is multidimensional. Shade can reduce incoming short-wave radiation, daily maximum air temperature and VPD, but the magnitude of each effect depends on crown geometry, leaf area, canopy height and the movement of air through the stand. Kohl *et al.* (2024), comparing eight common Ghanaian shade-tree species, found species-specific differences in below-canopy microclimate and cocoa growth. *Mangifera indica* and *Milicia excelsa* were among species producing strong microclimatic buffering, whereas cocoa growth responses did not map perfectly onto the species with the strongest cooling. This decoupling is expected because growth integrates light availability, water, nutrients, root interactions, pests and prior management. It also demonstrates why a single microclimate metric should not be used as a surrogate for climate resilience.

A further limitation of much climate-resilience evidence is timescale. Studies lasting one to three seasons can quantify immediate buffering, but cocoa is a long-lived perennial and shade trees become larger, more competitive and more valuable over decades. Canopy closure and root interactions evolve with stand age; pruning changes functional relationships; and farmers selectively remove trees that they perceive as harmful. Long-term evidence from Central Cameroon shows that cocoa agroforests can remain productive over extended periods when stand structure is actively renewed and associated trees are managed rather than treated as static background vegetation (Saj *et al.*, 2017). The implication is that resilience resides partly in management capacity: the same species mixture can move from facilitative to competitive as crowns expand unless it is thinned or pruned.

Taken together, physiological and field evidence supports a conditional rather than categorical statement. Shade is most defensible as a climate-adaptation tool when it reduces damaging radiation and atmospheric demand without creating greater water or light limitation. Whether that condition is met depends on species traits, canopy architecture, seasonal phenology, soil water storage and drought intensity. This framing shifts the management target from maximum cooling towards balanced resource use.

4. From Shade Percentage to Functional Shade Design

4.1 Why Canopy Cover Alone Is an Incomplete Design Variable

Canopy cover remains useful because it is observable and can be monitored from the ground or remotely, but it compresses important structural differences. Two farms with the same percentage cover can differ in crown height, crown depth, leaf density, spatial aggregation, tree basal area, phenology and rooting. Those differences determine whether cocoa receives diffuse light or deep shade, whether air circulation is maintained, and whether shade-tree roots compete directly with cocoa. Accordingly, attempts to identify one globally optimal shade percentage are vulnerable to hidden heterogeneity.

The empirical literature illustrates this problem. In Indonesian cacao agroforests, Gras *et al.* (2016) found that marketable yield in untreated control trees peaked around 30-40% canopy cover, and predator effects changed along the shade gradient. This is useful evidence for that system, but the study does not establish a universal target because the measured optimum incorporated local species composition, climate, cocoa material, pest community and forest proximity. In Ghana, four years of observations across 86 farm plots showed increasing yield with canopy cover up to approximately 30% in the studied agroecological zones (Asare *et al.*, 2019). Other datasets have reported yield penalties with increasing shade or benefits only under particular species. The apparent disagreement is better interpreted as evidence that canopy cover is a context-dependent proxy for multiple processes rather than a direct causal treatment with a universal dose-response curve.

Recent trait-based research provides a stronger design language. Isaac *et al.* (2024) synthesised relationships between shade-tree traits and agroecosystem functions, emphasising traits associated with litter decomposition, microclimate, carbon storage and crop productivity. For cocoa, whole-tree architecture is especially important because the vertical separation between the shade crown and cocoa canopy determines how much light competition occurs for a given amount of nominal cover. Blaser-Hart *et al.* (2021) showed that low-crown trees in Ghana reduced incoming light and were associated with lower cocoa yield, whereas elevated-crown trees had neutral yield effects, stored more aboveground carbon and still buffered temperature and VPD. The study converts a broad principle - retain shade - into a more actionable one: favour crown architectures that deliver environmental buffering from above the cocoa canopy while preserving productive light.

Leaf phenology adds a seasonal dimension. Cocoa climate stress is often concentrated in dry seasons, so shade that is desirable during the hottest period may be less desirable when water is critically scarce or when radiation is already low. Abdulai *et al.* (2025) classified Ghanaian shade trees into phenological functional groups and found that leaf-retention strategy influenced microclimate, soil water, cocoa physiology and yield. In that setting, the fully deciduous group produced the most favourable overall climate-resilience outcomes. The mechanism is plausible: seasonal leaf loss can reduce shade-tree transpiration and competition at times of water shortage while allowing denser foliage when radiative protection is more valuable. Yet a single phenological class should not be exported uncritically to humid regions with different dry-season timing, disease pressure or wind exposure.

4.2 Rooting, Litter and Nutrient Complementarity

Functional design must extend below ground. Root depth and distribution influence competition for water and nutrients, while litter quantity and chemistry influence decomposition and nutrient return. The Sulawesi desiccation experiment demonstrated contrasting root distributions between cocoa and *Gliricidia*, suggesting potential water-use complementarity (Moser *et al.*, 2010). By contrast, the Ghana extreme-drought study indicates that other tree-cocoa combinations can intensify soil-water competition (Abdulai, Vaast, *et al.*, 2018). Root complementarity is thus an empirical property of a species combination and soil profile, not an automatic benefit of species diversity.

Nutrient claims require similar restraint. Shade trees are often assumed to improve soil fertility through litterfall, nitrogen fixation and deeper nutrient capture. In Ghana, Blaser *et al.* (2017) found local positive effects of shade trees on some soil properties beneath individual crowns, but those benefits did not necessarily translate into whole-plot fertility gains sufficient to offset production costs. In Cameroon, Sauvadet *et al.* (2020) showed more clearly that the influence of shade trees on soil multifunctionality was species- and litter-trait dependent. Shade trees generally altered soil fertility indicators, yet the magnitude and direction varied with functional characteristics, while cocoa yield remained comparatively stable across the tested tree environments. Together, these studies replace the vague proposition that 'trees improve soil' with a more testable one: trees alter nutrient cycling according to their litter chemistry, biomass production, root turnover and spatial distribution.

Species-specific yield studies support the same conclusion. Across Ghanaian low-input farms, Asitoakor *et al.* (2022) compared cocoa under eight commonly retained tree species with unshaded control areas. Cocoa near *Cedrela odorata*, *Khaya ivorensis*, *Terminalia superba* and *Milicia excelsa* produced higher yields in the major crop season than the unshaded controls, even though some soil-nutrient indicators did not improve in parallel. The study is valuable because it moves beyond generic shade classes, but it remains an on-farm comparison in one region; species rankings may change with soil, rainfall, age and management.

4.3 A Functional Portfolio Rather Than a Single 'Best' Tree

No single shade-tree species is likely to optimise all functions. Tall, high-biomass trees can provide carbon storage and high crowns but may create windthrow risk or strong root competition. Nitrogen-rich litter can accelerate nutrient cycling but may not maximise long-term carbon retention. Dense evergreen crowns may cool effectively while increasing humidity and light limitation. Fruit or timber trees can diversify income but may be selected for market value rather than ideal crop complementarity. Functional diversity can therefore be valuable when different species perform complementary roles, provided the combined canopy does not exceed resource limits.

Farmer preferences should be treated as design evidence rather than an obstacle to technically ideal systems. In Ghana, Asigbaase *et al.* (2025) found that farmers' shade-tree choices reflected local ecological knowledge as well as production stage, information access and socioeconomic conditions. Trees are retained or removed because farmers observe shade, litter, branch fall, cocoa performance, product value and management burden over years. Scientific trait databases can formalise these observations, but they cannot substitute for local knowledge of storm behaviour, harvesting constraints or marketability. The most robust design process is therefore co-learning: functional ecology narrows plausible options, and farmer experience tests whether those options are operationally viable.

Table 2 synthesises the principal shade-design variables and shows why management should be expressed as a portfolio of traits rather than a single percentage canopy target. The same variable can create a benefit under one climatic condition and a cost under another, so monitoring must focus on both cocoa response and the resource pathway through which shade is acting.

Table 2. Mechanisms by which shade-tree design shapes cocoa climate resilience

Design variable	Potential benefit	Countervailing risk	Context or monitoring indicator	Supporting references
Crown height and vertical separation	Elevated crowns can buffer temperature and VPD while reducing direct light competition; large stems also add biomass carbon.	Low crowns can suppress cocoa light capture; very large trees can increase windthrow, pruning and access risks.	Crown-base height, PAR at cocoa canopy, crown spread, cocoa yield and wind exposure.	(Blaser-Hart *et al.*, 2021; Isaac *et al.*, 2024)
Canopy density and cover	Moderate cover can reduce radiative heat load and evaporative demand and may conserve soil moisture.	Excessive closure can depress photosynthesis, increase humidity and complicate disease management.	PAR, leaf and air temperature, VPD, relative humidity, soil moisture and disease incidence.	(Asare *et al.*, 2019; Gras *et al.*, 2016; Mensah *et al.*, 2023)
Leaf phenology	Seasonal leaf loss can increase light transmission when cocoa demand is high and reduce tree water use during dry periods.	If leaf loss coincides with damaging heat, cocoa may lose thermal protection when it is most needed.	Leaf-on/leaf-off calendar relative to dry season, flowering and pod filling; sap flow and microclimate.	(Abdulai *et al.*, 2025)
Root distribution and water-use strategy	Depth partitioning or conservative water use may reduce direct competition and improve system-level drought performance.	Shallow or highly transpiring trees can deplete shared soil water and magnify severe drought stress.	Root profiles, soil moisture by depth, sap flow, predawn water status and dry-season mortality.	(Abdulai, Vaast, *et al.*, 2018; Moser *et al.*, 2010)
Litter quantity and chemistry	High-quality or complementary litter can enhance nutrient cycling and selected soil functions.	Benefits can be slow, spatially localised or insufficient to offset crop nutrient export.	Litterfall, litter traits, soil C and N, available P, pH and cocoa nutrient status.	(Blaser *et al.*, 2017; Sauvadet *et al.*, 2020)
Species and product portfolio	Diverse useful trees can diversify products, spread climatic and market risk, and retain habitat structure.	Additional products can create labour, harvesting, tenure and market burdens that negate expected benefits.	Tree products sold or consumed, labour demand, market access, tenure security and net income.	(Asigbaase *et al.*, 2025; Quaedvlieg & Lagneaux, 2026)

Note. VPD = vapour pressure deficit; PAR = photosynthetically active radiation; C = carbon; N = nitrogen; P = phosphorus. Relationships are conditional on species, site and management and should not be interpreted as universal effects

5. Yield, Resource Competition, Soil Fertility and Biotic Regulation

5.1 Yield Is a Conditional Outcome, Not a Direct Measure of Sustainability

Yield remains indispensable because smallholders cannot maintain agroforestry systems that chronically fail to produce saleable cocoa. Yet yield response to shade is heterogeneous across the literature. Niether *et al.* (2020), synthesising direct agroforestry-monoculture comparisons, reported lower cocoa yield on average in agroforestry, while total system production, carbon and several environmental outcomes favoured diversified systems. That average is informative but conceals important variation in input intensity, cocoa genotype, shade composition and climate. It should not be interpreted as proof that shade necessarily causes economically unacceptable yield loss.

Several field studies demonstrate this variation. Abou Rajab *et al.* (2016) compared three Sulawesi cocoa systems with differing shade complexity and found a large increase in biomass carbon from monoculture to multi-shade systems without a detectable difference in cocoa bean yield. The study had only three replicate stands per system, so its strong 'no yield penalty' result has limited external validity; nonetheless, it is a useful counterexample to the assumption that more trees invariably reduce cocoa yield. In Central America, Somarriba *et al.* (2013) observed a non-linear relationship between carbon and cocoa yield across 229 plots, showing that intermediate configurations could combine substantial carbon stocks with production. In Ghana, Asare *et al.* (2019) found positive yield associations with canopy cover within their sampled range, whereas Abdulai, Jassogne, *et al.* (2018) found that low shade produced a yield advantage mainly in the wetter study region. These findings indicate that the production function is shaped by climatic and management context.

Long-term stand dynamics further complicate cross-sectional interpretation. Saj *et al.* (2017) analysed mature central Cameroonian agroforests and showed that productive longevity can be maintained through stand structure, cocoa densification, rejuvenation and management of associated trees. Yield comparisons made at one stand age can therefore misrepresent life-cycle performance. Full-sun or lightly shaded systems may deliver high early yield under fertilisation and crop protection but also experience faster canopy stress, greater weed pressure or more rapid decline; diversified systems may develop more slowly but provide additional products and ecological buffering. Definitive comparison requires multi-year or full-cycle measures rather than one harvest season.

5.2 Light, Water and Nutrients Create Moving Trade-offs

The physiological basis of yield trade-offs is straightforward in principle but difficult to parameterise in heterogeneous farms. Cocoa photosynthesis and reproductive growth require adequate light, so excessive shade can reduce carbon assimilation and flower or pod development. Conversely, high radiation increases leaf temperature and atmospheric demand, potentially closing stomata and reducing carbon gain during water stress. The 'optimal' light environment therefore moves with soil moisture and temperature. Shade also affects the thermal environment of flowers, pests, pollinators and pathogens, further separating physiological potential from harvested yield.

Water competition can reverse the expected direction of shade effects. During severe drought, shade-tree transpiration may reduce soil-water availability more than canopy cooling reduces cocoa demand, as observed by Abdulai, Vaast, *et al.* (2018). Under less extreme conditions, shade can conserve soil moisture by reducing radiation and evaporative demand, as in Mensah *et al.* (2023). Root traits and pruning are likely to mediate this balance. Pruning reduces leaf area and transpiration as well as shade intensity; species with deeper roots may access water less directly contested by cocoa; and deciduous species may partially withdraw from competition during dry periods. These hypotheses have strong mechanistic plausibility but remain under-tested in replicated multi-species experiments.

Soil fertility is another domain where simplified claims can mislead. Shade-tree litter can increase organic inputs and alter nutrient cycling, but fertility benefits are spatially concentrated and depend on litter quality, decomposition, nutrient export in harvested products and external inputs. Blaser *et al.* (2017) cautioned that positive microsite effects beneath trees did not become uniform farm-scale fertility improvements. Sauvadet *et al.* (2020) showed that litter traits explained meaningful differences among shade species. Consequently, shade management should be integrated with nutrient budgets rather than marketed as a replacement for fertility management.

5.3 Pests, Disease and Biological Control

Shade modifies both natural enemies and crop pathogens, making biotic regulation one of the least transferable outcomes. In Sulawesi, Gras *et al.* (2016) experimentally excluded ants, birds and bats across a shade gradient. Ant exclusion reduced yield especially under low shade, while bird effects changed direction with canopy cover and bat exclusion had no measurable yield effect. The study demonstrates that predator guilds respond differently to shade and that biodiversity cannot be assumed to translate monotonically into crop protection. It also provides unusually strong causal evidence because predator access was manipulated rather than inferred from abundance correlations.

Disease creates a different trade-off. Humid, shaded conditions can favour *Phytophthora* infection, while excessive exposure may increase physiological stress and susceptibility to other pests. Asitoakor *et al.* (2024) monitored mirids and black pod disease in Ghana beneath eight shade-tree species and unshaded areas. Tree species differed in their associations with mirid abundance and disease; *Cedrela odorata*, *Khaya ivorensis* and *Milicia excelsa* were associated with relatively low mirid occurrence, whereas *Cola nitida* and *Triplochiton scleroxylon* were less favourable in the observed pest-disease context. Black pod was strongly related to rainfall and humidity, whereas mirids tracked temperature. These results reinforce the argument for species-specific integrated pest management rather than treating 'shade' as one categorical treatment.

The main caution is that pest and disease effects are pathosystem-specific. A shade structure that suppresses one insect may increase leaf wetness or humidity favourable to a pathogen. Regional disease prevalence also changes the risk calculus. A humid zone with recurrent black pod may require more open crowns, sanitation and air movement than a hotter dry zone where thermal buffering is the dominant concern. Climate warming can further rearrange pest and pathogen pressure, so static shade prescriptions may become obsolete.

The representative evidence in Table 3 highlights why apparently conflicting yield findings can be reconciled when design, climate and mechanism are considered together. It also shows a recurring methodological weakness: many studies are observational or compare a small number of stand types, whereas relatively few manipulate both shade structure and climate over multiple years.

Table 3. Representative evidence on yield, water relations, soil fertility and biotic regulation

Study context or design	Main finding	Critical limitation or caution	Management implication	Supporting references
Ghana; full sun versus two shade-tree species across wet to extreme-drought conditions	Under extreme drought, shaded cocoa experienced stronger water stress and mortality, indicating that tree competition can overwhelm microclimate benefits.	Only selected tree species and one climatic episode were represented; the result does not apply to all shade assemblages.	Drought adaptation requires species-specific hydrological screening rather than shade presence alone.	(Abdulai, Vaast, *et al.*, 2018)
Ghana; 33-month rain-suppression experiment with 40% shade versus full sun	Shade improved soil water status, physiology, growth and yield relative to full sun, but did not remove drought damage.	One standardised shade level cannot resolve species- and architecture-specific effects.	Moderate shade can be beneficial under water limitation but should be coupled with drought-tolerant design and monitoring.	(Mensah *et al.*, 2023)
Ghana; low-input farms comparing common retained tree species	Several shade-tree species were associated with improved cocoa yield relative to unshaded controls, with strong species specificity.	On-farm heterogeneity and species-site associations complicate causal interpretation.	Extension should recommend locally validated species portfolios, not undifferentiated tree retention.	(Asitoakor *et al.*, 2022)
Indonesia; faunal exclusions and shade gradients	Ants, birds and bats had contrasting effects on cocoa production components, showing that biological control is not reducible to biodiversity richness alone.	Taxon effects and shade responses are context-dependent and may shift with farm management.	Retain habitat while evaluating functional guilds and net crop effects rather than assuming all associated biodiversity is beneficial.	(Gras *et al.*, 2016)
Ghana; two-year pest and disease monitoring beneath eight tree species	Mirid damage and black pod infection varied among shade-tree species and climatic conditions.	Disease and pest outcomes were measured in a specific production zone and species set.	Shade-tree choice can form part of integrated pest management, but species-specific disease risks must be monitored.	(Asitoakor *et al.*, 2024)
Central Cameroon; tree-species comparison across cocoa farms	Shade-tree litter traits explained variation in soil-function indicators; high-quality litter did not translate into a simple universal yield response.	Soil responses were measured in poor sandy soils and cannot be generalised without soil context.	Select trees for nutrient-cycling traits alongside water, light and product functions.	(Sauvadet *et al.*, 2020)
Central Cameroon; long-term farm analysis	Long-lived cocoa agroforests maintained production through stand renewal and changing tree structure, demonstrating that temporal management matters.	Observational long-term trajectories integrate many concurrent management changes.	Evaluate agroforestry over full stand lifecycles rather than using short-term yield snapshots.	(Saj *et al.*, 2017)

Note. The table highlights representative studies chosen for contrasting mechanisms and designs; it is not an exhaustive inventory of the cocoa agroforestry literature

6. Carbon Mitigation, Permanence and Land-Use Baselines

Carbon is among the most consistently demonstrated ecological advantages of retaining trees in cocoa farms, but interpretation depends on the pool measured and the baseline against which agroforestry is compared. Aboveground biomass carbon rises as shade-tree density, basal area and tree size increase because cocoa monocultures simply contain less woody biomass. The more difficult questions concern soil organic carbon (SOC), the permanence of stored carbon, greenhouse-gas emissions from farm inputs, and whether agroforestry is being established on degraded agricultural land or by thinning natural forest.

6.1 Aboveground Carbon: Strong Direction of Effect, Variable Magnitude

Across cocoa landscapes, the direction of the aboveground-carbon effect is robust. Somarriba *et al.* (2013), analysing 229 Central American plots, estimated a mean total carbon stock of 117 ± 47 Mg ha−1 across biomass, soil and dead organic pools, with substantial contributions from shade and associated trees. The study also showed that cocoa yield and carbon were related non-linearly, creating configurations in which relatively high carbon could be retained without proportionate yield loss. The magnitude should not be generalised directly to other regions because tree size, stand age, soil carbon, species composition and land-use history differed among sites.

Dawoe *et al.* (2016) found strong spatial variation in aboveground carbon across Ghanaian cocoa landscapes and reported that shade trees and cocoa trees contributed roughly similar shares to standing tree carbon on average. Their survey also documented high shade-tree taxonomic richness across districts, although local stand diversity was lower than numbers aggregated across the full landscape might suggest. The carbon implication is straightforward: retaining large trees matters disproportionately because biomass scales non-linearly with stem diameter. It follows that tree density alone is an incomplete carbon indicator; a small number of large, high-crown trees may store more carbon than many small stems and can impose a different pattern of competition on cocoa.

Stand-level comparisons provide complementary evidence. Abou Rajab *et al.* (2016) observed roughly a fivefold gradient in total biomass carbon between unshaded and diverse-shade cacao systems in Sulawesi while cocoa yield remained similar. Because only nine stands were included, the study cannot establish that such compatibility is general, but it demonstrates biological feasibility. More recently, Krause *et al.* (2025) revisited a 14-year experiment in Bolivia and found higher biomass and SOC in agroforestry than cocoa monocultures, with the successional agroforestry treatment accumulating the largest biomass-carbon stocks. The long duration and experimental comparison give this evidence unusual value, although the highly managed successional system may not be readily transferable to smallholders without equivalent labour and pruning capacity.

Architecture again connects carbon with production. Blaser-Hart *et al.* (2021) found that elevated-canopy trees stored more carbon while avoiding the yield reductions associated with low crowns. This suggests a design route by which carbon and production objectives can be partially decoupled: carbon can be concentrated in taller stems and crowns positioned above the productive cocoa canopy rather than in dense low foliage that competes directly for light. The concept remains subject to wind stability, timber rights and species availability, but it is more mechanistically defensible than maximising tree numbers per hectare.

6.2 Soil Carbon Is More Heterogeneous Than Biomass Carbon

SOC responses are less consistent because soils integrate historical land use, texture, mineralogy, erosion, litter inputs, root turnover and management over long periods. Agroforestry can increase organic inputs, but a standing tree does not guarantee measurable additional SOC within the depth and duration sampled. Niether *et al.* (2020) found much less consistent agroforestry effects on soil indicators than on carbon stored in woody vegetation. Blaser *et al.* (2017) likewise showed that local fertility effects beneath shade trees may not scale to whole plots. In the Bolivia long-term experiment, Krause *et al.* (2025) detected SOC gains in some agroforestry treatments, illustrating that soil responses may emerge over longer timescales and vary among organic-matter fractions.

This distinction has practical consequences for carbon accounting. Aboveground tree biomass can be estimated using inventories and allometric models, whereas SOC requires repeated, depth-consistent sampling with bulk density and equivalent-soil-mass considerations if changes are to be attributed reliably to management. Programmes that treat a generic agroforestry conversion factor as evidence of soil-carbon gain risk overstating mitigation. Carbon claims should therefore separate biomass carbon, dead organic matter and SOC, state the baseline, and acknowledge uncertainty.

6.3 Net Greenhouse-Gas Balance and Economic Co-benefits

Biomass carbon is only one component of climate mitigation. Fertiliser can generate nitrous oxide emissions, land-use change can create large carbon debts, and farm operations have energy costs. Hawkins *et al.* (2024) combined greenhouse-gas accounting with production value in Ghana and found that hybrid cocoa under moderate shade, defined in their typology as 13-25 shade trees ha^{-1}, had a more favourable net greenhouse-gas balance and higher average value of production than the compared full-sun hybrid and Amazonia systems. This result is noteworthy because it jointly evaluates mitigation and economic performance. It remains observational, however, and the numerical shade range reflects a particular region, variety mix and management environment; it should not be converted into a global standard.

Carbon permanence is another unresolved issue. Stored biomass can be lost rapidly when trees are harvested, storms damage canopies, cocoa farms are replanted or land is converted. Tenure and tree-ownership rules influence whether farmers are willing to retain valuable timber trees for decades. Carbon programmes therefore need to reward not only initial tree establishment but also retention, replacement and adaptive canopy management. A climate-resilient design may deliberately remove or prune a tree that has become too competitive; rigid carbon targets can conflict with agronomic adaptation if they reward stem retention regardless of crop effects.

6.4 Agroforestry Carbon Is Not a Licence for Forest Conversion

The land-use baseline is ethically and biophysically decisive. A cocoa agroforest established on degraded pasture can increase tree cover, habitat complexity and carbon. The same cocoa agroforest established by thinning primary or mature secondary forest represents a substantial loss of forest carbon and biodiversity even if it retains many trees. Maney *et al.* (2022) found that biodiversity outcomes differed according to whether agroforests were derived from forest or open land, underscoring the importance of transition pathway. Earlier landscape reviews similarly warned that cocoa agroforests can contribute to conservation within agricultural mosaics without substituting for intact forest (Clough *et al.*, 2009; Schroth & Harvey, 2007).

This baseline principle changes how 'climate-smart cocoa' should be evaluated. The relevant comparison is not only agroforestry versus full-sun cocoa. It is also forest retained versus forest converted, degraded land restored versus degraded land left open, and existing agroforest maintained versus simplified. Agroforestry can be a mitigation strategy when it raises or conserves carbon within already agricultural land; it is not a justification for expanding cocoa into high-carbon ecosystems.

7. Biodiversity Conservation and Landscape Context

Biodiversity is often the most visible ecological argument for cocoa agroforestry, yet the evidence supports a hierarchy rather than a binary distinction. Structurally complex cocoa generally supports more species and more forest-associated organisms than simplified full-sun cocoa or open agricultural land, but primary forest remains the highest-value habitat for many taxa. Management intensity, shade-tree diversity, pesticide use and distance to forest all shape the position of a farm within that hierarchy (De Beenhouwer *et al.*, 2013; Schroth & Harvey, 2007).

7.1 Habitat Complexity and Community Intactness

The global meta-analysis by De Beenhouwer *et al.* (2013), covering coffee and cacao, showed that intensification reduces species richness and ecosystem-service indicators. Its broad geographic reach supports the generality of the direction of effect, although combining crops and taxa necessarily increases heterogeneity. Cocoa-specific landscape modelling by Maney *et al.* (2022) refined the interpretation: biodiversity intactness was higher in cocoa agroforests than in open-land systems, but lower than in primary forest, and forest-derived agroforests retained more intact communities than agroforests established on previously open land. This means biodiversity value cannot be inferred from shade cover alone; historical continuity and source populations in the surrounding landscape matter.

Cocoa agroforests can serve as supplementary habitat, movement corridors and buffer zones, particularly when connected to forest remnants. Yet some species tolerate agroforestry because they are ecological generalists, while disturbance-sensitive specialists may disappear even in heavily shaded farms. Aggregate richness can therefore mask compositional replacement. A farm might have many species but fewer forest specialists. Conservation assessment should consequently include community composition or intactness, not simply species counts.

Recent work continues to emphasise scale. Higuera-Mora *et al.* (2026), studying 32 Colombian cocoa agroecosystems, linked farm-level vegetation structure and biodiversity with surrounding landscape fragmentation and performance indicators. The study is cross-sectional and geographically limited, but its multi-scale framing is important: a well-designed farm embedded in an extensively deforested matrix may not support the same fauna as a similar farm adjoining forest. Conversely, landscape connectivity may increase the conservation value of moderate on-farm shade.

7.2 Biodiversity as Function Versus Biodiversity as Conservation Value

Two arguments for biodiversity should be separated. The first is instrumental: diverse organisms can pollinate, regulate pests, decompose litter or otherwise support production. The second is intrinsic or conservation-oriented: farms can retain species regardless of whether each species increases cocoa yield. Mixing the two creates unrealistic expectations that every conserved taxon must provide a measurable service.

Gras *et al.* (2016) provides a useful functional example. Ants enhanced yield in much of the shade gradient, bird effects changed direction with canopy cover, and bats showed no detectable yield effect in that experiment. The findings reveal ecological interactions rather than a simple 'more predators equals more cocoa' relationship. The absence of an immediate yield effect does not make bats or particular bird species valueless from a conservation perspective. It instead shows that biodiversity service delivery depends on food-web context.

Shade trees themselves contribute directly to plant diversity, but species identity matters. Dawoe *et al.* (2016) recorded more than one hundred shade-tree species across Ghanaian districts, yet a few species were common and individual farms were much less diverse than landscape totals. Farmer selection tends to favour trees with timber, food, medicinal, cultural or agronomic value. This can conserve useful native species but can also homogenise stands if extension programmes distribute a narrow set of preferred seedlings. Trait-based selection should therefore avoid becoming a new route to uniformity. A portfolio can be designed around complementary traits while maintaining taxonomic diversity and native species where appropriate.

7.3 Biodiversity-Yield Trade-offs Are Not Fixed

The biodiversity-yield relationship is sometimes framed as an inevitable trade-off in which greater shade and diversity reduce cocoa yield. The evidence is more conditional. Jezeer *et al.* (2017), synthesising shaded coffee and cocoa systems, found lower average crop yields under shade but also lower costs, higher product prices in some cases and potentially greater profitability. The biodiversity literature also indicates that intermediate shade can retain substantial ecological value without the strongest production penalties. Still, few studies jointly measure biodiversity, yield, profit and climate resilience in the same farms, so purported 'win-win' configurations are often assembled by comparing different studies rather than demonstrated within one design.

This gap is particularly important under warming. Shade structures chosen for biodiversity may increase humidity and disease risk in already wet zones; structures chosen primarily for cooling may favour a subset of tall, fast-growing trees that deliver less habitat diversity than mixed native canopies. Landscape conservation may sometimes be achieved more effectively by combining moderately shaded productive farms with protected forest blocks rather than demanding maximal tree diversity within every cocoa plot. The appropriate strategy depends on which taxa and ecosystem functions are conservation priorities.

Table 4 summarises the relative confidence that can be placed in carbon and biodiversity conclusions. The evidence is strongest for additional aboveground biomass carbon and for higher biodiversity relative to open systems. It is weaker for universal SOC gains, universal pest suppression and any claim that agroforestry can replace intact forest.

Table 4. Carbon and biodiversity outcomes under cocoa agroforestry

Domain	Comparatively robust pattern	Key heterogeneity or caveat	Planning implication	Supporting references
Aboveground carbon	Adding and retaining trees consistently increases woody biomass carbon relative to simplified cocoa systems.	Magnitude depends on tree density, size, species, stand age and pruning; high carbon does not guarantee high cocoa yield.	Use stand structure and long-term biomass dynamics, not tree count alone, when estimating mitigation value.	(Abou Rajab *et al.*, 2016; Dawoe *et al.*, 2016; Krause *et al.*, 2025; Somarriba *et al.*, 2013)
Soil organic carbon	Agroforestry can increase soil carbon in some long-term systems through litter, roots and reduced disturbance.	Cross-system syntheses report weaker and less consistent soil responses than biomass responses; depth and baseline strongly affect estimates.	Separate biomass and soil pools and standardise soil depth, bulk density and baseline comparisons.	(Krause *et al.*, 2025; Niether *et al.*, 2020)
Net greenhouse-gas performance	Moderate-shade systems can improve farm-level greenhouse-gas balance when added tree carbon is retained.	Input use, land-use history, tree longevity, leakage and carbon accounting boundaries can reverse apparent benefits.	Carbon claims require explicit baselines, permanence assumptions and full-system accounting.	(Hawkins *et al.*, 2024; Vaast & Somarriba, 2014)
Biodiversity relative to open cocoa or monoculture	Structural and floristic complexity generally supports higher richness or intactness than open agricultural systems.	Responses vary among taxa, and biodiversity effects may be confounded by surrounding habitat and management intensity.	Prioritise structurally diverse, low-disturbance agroforestry on existing farmland where it complements habitat protection.	(De Beenhouwer *et al.*, 2013; Maney *et al.*, 2022; Niether *et al.*, 2020)
Biodiversity relative to intact forest	Agroforests retain important conservation value but do not replace primary or intact forest communities.	Species richness can obscure losses of forest specialists and shifts in community composition.	Avoid framing cocoa agroforestry as ecological compensation for forest conversion.	(Maney *et al.*, 2022; Schroth & Harvey, 2007)
Landscape history and connectivity	Agroforest conservation value depends on whether it retains forest structure or restores trees in previously open land and on surrounding habitat connectivity.	Farm-scale measures can misclassify conservation value when land-use history and landscape configuration are ignored.	Target both on-farm habitat quality and landscape connectivity, and distinguish retention from restoration pathways.	(Higuera-Mora *et al.*, 2026; Maney *et al.*, 2022)

Note. Carbon and biodiversity gains are evaluated relative to the stated comparator. Agroforestry benefits on existing agricultural land should not be used to justify conversion of intact forest

8. Farm Economics, Adoption and Governance

The ecological literature can identify potentially advantageous shade configurations, but adoption depends on whether farmers can establish, maintain and benefit from them. This is not a secondary implementation issue. Labour, tenure, credit, tree ownership, access to seedlings, extension advice, markets for fruit and timber, and cocoa price volatility can determine which ecological designs are feasible. Economic evaluation that uses cocoa yield as the sole outcome therefore misses the mechanisms through which agroforestry succeeds or fails.

8.1 Yield, Costs and Net Returns

Jezeer *et al.* (2017) found that shaded coffee and cocoa systems could be financially competitive despite lower yields because production costs and price premiums altered profitability. The inclusion of coffee limits cocoa-specific inference, but the analytical lesson is sound: net revenue and benefit-cost performance are more relevant to household decisions than biological yield alone. In

Ghana, Owusu *et al.* (2022) similarly showed that farmer perceptions of ecological benefits were linked with shade decisions and that economic performance varied among shade levels. The study underscores that preferences are not purely agronomic; farmers evaluate risk, labour and multiple outputs.

More recent evidence strengthens this point. Dekegel *et al.* (2026), combining household and ecological plot data from 313 cocoa-farming households in southern Bahia, found that higher shade-tree density was associated with lower cocoa yield but also lower production costs, leaving net cocoa income broadly unaffected. Revenue from other agroforestry crops did not fully compensate for all trade-offs, and smaller farms appeared better able to absorb some of the effects. This result challenges both sides of the simplification debate: lower yield under shade need not imply lower net cocoa income, but diversification products should not be assumed to deliver sufficient cash automatically.

Hawkins *et al.* (2024) likewise found a Ghanaian moderate-shade hybrid typology that combined favourable greenhouse-gas removal with comparatively high value of production. These observational studies cannot rule out selection bias, because farmers who manage moderate shade may differ in skill, inputs, cocoa variety or market access. Nevertheless, they demonstrate why future trials should record labour and financial outcomes alongside biophysical measures.

8.2 Why Technically Promising Agroforestry Is Not Automatically Adoptable

Adoption studies reveal a gap between recommended systems and farmer incentives. Kaba *et al.* (2020), interviewing cocoa farmers in Ghana's semi-deciduous forest zone, found widespread experience with shade trees but also active tree removal motivated partly by expectations of higher cocoa yield and by limited understanding of particular shade benefits. Education, experience and perceptions influenced whether farmers retained recommended tree numbers. Such studies are vulnerable to self-reporting and local sampling, yet they identify the institutional pathway through which scientific recommendations become actual canopy structure.

Asigbaase *et al.* (2025) showed that Ghanaian farmers possess differentiated ecological knowledge of shade species and choose trees according to observable attributes and socioeconomic circumstances. This knowledge is especially relevant where formal trait measurements are unavailable. Extension that gives a fixed species list without incorporating local experience can fail because farmers face branch-fall hazards, difficult harvesting, timber restrictions, competition, fire risk or poor by-product markets that are not captured in experimental plots.

A particularly relevant recent critique comes from Madre de Dios, Peru. Quaedvlieg and Lagneaux (2026) examined promoted cacao agroforestry models and found that low cacao yields, limited knowledge of complex systems, labour constraints and weak markets for by-products undermined the promised sustainability benefits. Their qualitative case study should not be generalised to all Latin American cocoa, but it exposes a recurring policy error: treating 'agroforestry' as a technology package whose ecological reputation guarantees livelihood success. Complex designs create management demand. If projects subsidise establishment but not long-term pruning, market development or learning, farmers may simplify the system or abandon cocoa.

8.3 Tenure, Tree Rights and Incentive Alignment

Shade trees are long-lived assets, and rights to plant, harvest or sell them determine whether farmers perceive them as assets or liabilities. Where timber trees are legally difficult to harvest, retaining them can impose opportunity costs without a clear revenue pathway. Conversely, secure rights can make high-value timber a long-term savings mechanism. Carbon or biodiversity payments can strengthen incentives, but only if transaction costs, monitoring requirements and permanence obligations are compatible with smallholder realities.

Incentive design must also avoid locking farmers into ecologically inappropriate shade. A payment based exclusively on tree count can reward dense, low-value or competitive stems. A carbon contract that discourages adaptive pruning can reduce crop resilience during severe drought. Certification that specifies a generic canopy percentage may be easier to audit but less agronomically defensible than functional criteria. The policy challenge is to create measurable indicators that preserve flexibility: for example, minimum structural diversity or carbon thresholds combined with evidence of canopy maintenance, species suitability and forest protection.

8.4 Equity and Risk Distribution

Agroforestry transitions involve temporal risk. Shade trees may require years before providing timber or fruit, while cocoa yield effects occur sooner. Wealthier farmers can tolerate delayed returns, hire pruning labour or absorb experimental failure more easily than households operating near subsistence constraints. Credit and extension therefore influence not just adoption rates but the distribution of climate resilience. Programmes that assume uniform capacity can unintentionally shift management risk onto farmers while downstream supply chains claim sustainability benefits.

Climate risk further complicates incentives. Wätzold *et al.* (2026), using household panel data and satellite-derived climate information in Ghana, found that agroforestry adopters were on average less affected by rainfall decline, but the adaptation benefit was consistent mainly in climatically suitable cocoa-growing zones and not significant in more drought-prone, less suitable regions. This result aligns with the physiological evidence: agroforestry can buffer stress within a range, but cannot be assumed to overcome severe climatic unsuitability. Subsidies for shade establishment in marginal zones therefore need to be paired with diversification and, where necessary, planned transition to alternative crops rather than framed as a guarantee of cocoa persistence.

Table 5 converts these ecological and socioeconomic findings into a climate-contingent decision framework. It is not a prescriptive recipe; its purpose is to identify which shade functions should be prioritised under contrasting constraints and which failure modes should be monitored.

Table 5. Climate-contingent decision framework for shade management

Dominant farm condition	Shade-design priority	Monitoring indicators	Main failure mode to avoid	Supporting references
High heat or VPD with adequate soil water	Retain or establish elevated crowns that reduce radiation and temperature without excessive lower-canopy light competition.	Leaf and air temperature, VPD, PAR, cocoa photosynthesis and yield.	Dense low crowns that cool the stand but suppress crop light capture.	(Blaser-Hart *et al.*, 2021; Kohl *et al.*, 2024)
Seasonal water deficit without chronic severe drought	Use moderate, adjustable shade and phenologies that reduce atmospheric demand while limiting dry-season tree water use.	Soil moisture by depth, sap flow, leaf water status, dry-season canopy phenology and yield stability.	Assuming microclimate cooling necessarily means improved plant water status.	(Abdulai *et al.*, 2025; Mensah *et al.*, 2023)
Severe drought or climatic margin	Prioritise drought-compatible species, root complementarity, water-conserving pruning and contingency planning for crop diversification or transition.	Mortality, predawn water status, deep soil moisture, multi-year yield and climate suitability.	Adding high-water-use trees where shared soil water is already the binding constraint.	(Abdulai, Vaast, *et al.*, 2018; Schroth *et al.*, 2016; Wätzold *et al.*, 2026)
Humid site with recurrent black pod or mirid pressure	Manage canopy aeration and choose species with locally favourable pest and disease associations.	Relative humidity, leaf wetness, black pod incidence, mirid damage and tree-species identity.	Increasing shade complexity without accounting for pathogen microclimate or pest host relationships.	(Asitoakor *et al.*, 2024; Gras *et al.*, 2016)
Carbon and biodiversity priority on existing cocoa land	Retain structurally complex trees, favour elevated biomass and habitat value, and maintain landscape connectivity.	Tree biomass, recruitment, mortality, habitat structure, community intactness and adjacent natural habitat.	Maximising on-farm carbon while ignoring forest-conversion baselines or specialist biodiversity loss.	(Krause *et al.*, 2025; Maney *et al.*, 2022; Schroth & Harvey, 2007)
Labour-, tenure- or market-constrained smallholder	Choose manageable species with valued products and align tree density with labour, rights, market access and farmer objectives.	Labour days, pruning burden, product sales, net income, tenure security and farmer retention of trees.	Promoting ecologically desirable designs that farmers cannot legally, economically or practically maintain.	(Asigbaase *et al.*, 2025; Dekegel *et al.*, 2026; Kaba *et al.*, 2020; Quaedvlieg & Lagneaux, 2026)

Note. VPD = vapour pressure deficit; PAR = photosynthetically active radiation. The framework is intended for diagnosis and adaptive design, not as a universal prescription

9. Integrating Objectives: A Climate-Contingent Framework for Cocoa Agroforestry

The evidence supports an integrated framework in which the design problem begins with the limiting factor rather than with a fixed shade target. A farm experiencing high midday temperature and VPD but adequate soil water requires a different canopy from a farm where prolonged dry-season soil-water depletion is the dominant risk. A humid farm with recurrent black pod requires different air movement and canopy phenology from a farm in a dry transition zone. The functional objective is to retain the environmental benefits of trees while preventing the most limiting resource from becoming more limiting.

The first design axis is vertical architecture. Elevated crowns are promising because they can store substantial biomass and moderate microclimate while reducing direct light competition with cocoa (Blaser-Hart *et al.*, 2021). This does not imply that all tall trees are suitable. Large trees can create windthrow risk, difficult pruning, root competition and harvesting hazards. Architecture must therefore be coupled with species-specific knowledge of root systems, crown spread and branch stability.

The second axis is seasonality. Leaf phenology determines when the crop is shaded and when the shade tree transpires most strongly. The Ghana evidence on phenological functional groups suggests that deciduous behaviour can improve seasonal complementarity (Abdulai *et al.*, 2025). In climates where the dry season coincides with damaging heat, complete leaf loss may reduce protection precisely when it is needed, so phenology must be matched to local rainfall and temperature calendars rather than ranked abstractly.

The third axis is below-ground complementarity. Deep-rooted or hydraulically conservative trees may coexist with cocoa more effectively than shallow, highly transpiring species during drought, but direct empirical data remain sparse. Monitoring of soil moisture at multiple depths, tree and cocoa sap flow, root distribution and predawn water status should therefore become part of species-screening trials. The contradiction between Abdulai, Vaast, *et al.* (2018) and Mensah *et al.* (2023) is best viewed as evidence that hydrological interactions define the boundary between beneficial shade and harmful competition.

The fourth axis is functional diversity. Species mixtures can distribute functions among trees: high crowns for carbon and microclimate, nutrient-rich litter producers for cycling, fruit trees for household consumption or cash, and habitat trees for biodiversity. Yet diversity has diminishing returns if total leaf area creates excessive shade or if each additional product lacks a market. The objective should be functional complementarity, not species accumulation for its own sake.

The fifth axis is adaptive management. Cocoa agroforests are dynamic. Canopies expand, cocoa trees age, pathogens emerge, climate changes and markets shift. Shade must therefore be pruned, thinned and renewed. A static certification threshold is poorly suited to a system whose optimal structure changes through time. Long-term Cameroonian evidence indicates that productive longevity depends on active stand renewal rather than passive preservation of an initial design (Saj *et al.*, 2017). Adaptive management should be recognised as a core component of resilience, not as deviation from an ideal plan.

Finally, the farm cannot be separated from the landscape. Conservation value and climatic buffering depend partly on forest remnants, riparian vegetation, neighbouring land uses and connectivity (Maney *et al.*, 2022). Farm-level agroforestry should therefore be nested within landscape strategies that protect intact forest, restore degraded corridors and prevent cocoa expansion into high-carbon habitats. The highest-value climate outcome may come from maintaining moderately shaded, profitable cocoa on existing farmland while enforcing forest conservation, rather than maximising shade inside farms without controlling frontier expansion.

10. Future Directions

The next phase of cocoa agroforestry research should move beyond comparisons of 'shaded' and 'unshaded' farms towards experiments that identify the mechanisms governing performance under climatic stress. The first priority is long-term factorial testing of shade-tree functional traits under controlled differences in water availability. Current evidence strongly implicates crown height, leaf phenology and rooting interactions, but these traits have rarely been manipulated together. Multi-site experiments should combine contrasting crown architectures and phenological groups with rainfall manipulation across wet, intermediate and drought-prone cocoa zones. Measurements should include radiation, leaf and air temperature, VPD, soil moisture by depth, sap flow, cocoa water potential, photosynthesis, growth, flowering, pod set, mortality and multi-year yield. Such designs would reveal when microclimate facilitation is overtaken by below-ground competition and would provide a mechanistic basis for region-specific species portfolios rather than generic shade recommendations (Abdulai, Vaast, *et al.*, 2018; Abdulai *et al.*, 2025; Mensah *et al.*, 2023).

A second immediate priority is to define climate resilience using longitudinal outcomes. Many studies infer resilience from a cooler microclimate or higher soil moisture, whereas farmers need farms that survive extremes, recover after them and maintain acceptable income. Trials should therefore follow pre-event performance, event-year damage and post-event recovery, with explicit measures of tree mortality, canopy loss, delayed pod production and replanting cost. Natural experiments following El Niño events, heatwaves and multi-year rainfall deficits can complement manipulative studies, but pre-event baseline data are essential to avoid attributing pre-existing farm differences to climate response. Long-term farm networks in Ghana, Côte d'Ivoire, Cameroon, Brazil, Peru, Ecuador, Indonesia and other producing regions would also reduce the current geographic concentration of evidence.

Third, shade-tree selection should be linked to directly measurable functional traits. Species lists are difficult to transfer because the same taxon can express different crown form, growth rate or leaf phenology under contrasting environments. Trait screening should quantify crown base height, crown radius, leaf area traits, seasonal leaf retention, wood density, rooting depth, fine-root distribution, transpiration strategy, litter nitrogen and phosphorus, decomposition rate and branch-failure risk. These traits should be connected to farmer-observable proxies wherever possible so that extension does not depend on laboratory measurements. The synthesis by Isaac *et al.* (2024) provides a useful conceptual base, but cocoa-specific validation across climate zones is still needed.

Fourth, research on carbon should distinguish additionality, permanence and pool-specific change. Aboveground biomass responses are relatively well established, whereas SOC remains uncertain and slow to detect. Long-term experiments should use consistent sampling depths, bulk density and equivalent-soil-mass calculations and should report changes in particulate and mineral-associated organic matter where feasible. Whole-farm greenhouse-gas accounting should include fertiliser-related nitrous oxide, land-use history and woody biomass dynamics rather than presenting standing tree carbon as a complete mitigation balance. Studies such as Hawkins *et al.* (2024) and Krause *et al.* (2025) demonstrate the value of integrating greenhouse-gas and long-term carbon outcomes, but replication across regions and production systems is needed.

Fifth, biodiversity assessment needs stronger linkage between habitat structure, community composition and ecosystem function. Species richness alone should be supplemented by forest-specialist representation, functional diversity, community intactness and landscape connectivity. Experiments that manipulate shade structure while measuring pollination, natural-enemy activity, disease and yield would clarify which biodiversity components provide agronomic services and which represent conservation value independently of crop performance. Landscape designs should compare farms embedded in intact, fragmented and highly simplified matrices because the same on-farm canopy can support different communities depending on surrounding habitat (Maney *et al.*, 2022). This work should be coordinated with forest-protection monitoring to ensure that gains within cocoa farms are not offset by expansion into natural ecosystems.

Sixth, pest and disease research should treat shade-tree identity and weather jointly. The species-specific findings of Asitoakor *et al.* (2024) show that recommendations based on total shade may miss important effects on mirids and black pod. Multi-year pathosystem studies should measure canopy wetness, humidity duration, spore or vector dynamics and natural enemies under different species combinations. Climate scenarios should be included because warming and altered rainfall can change both host susceptibility and pathogen development. The objective should be integrated pest and disease management that uses canopy design alongside sanitation, resistant planting material and targeted chemical or biological control rather than expecting shade to regulate all threats.

Seventh, economic studies should be embedded within biophysical experiments. Labour for pruning, harvesting and sanitation; establishment and replacement costs; yields of cocoa and associated products; price premiums; input expenditure; and risk of crop failure should be recorded from the start. Net present value and cash-flow timing are particularly important because trees impose costs before some benefits mature. Distributional analysis should test whether farm size, household labour, gendered access to land, credit and tenure alter the feasibility of particular designs. Evidence from Brazil and Peru shows that ecological complexity can create either manageable trade-offs or serious implementation barriers depending on costs, labour and markets (Dekegel *et al.*, 2026; Quaedvlieg & Lagneaux, 2026).

Eighth, adoption research should test alternative extension models rather than only documenting farmer perceptions. Participatory species selection, farmer-managed trials and co-designed pruning rules could be compared with conventional top-down recommendations. Outcomes should include persistence of shade trees after project support ends, not merely planting at project completion. Tree rights and tenure should be analysed as causal institutional variables because farmers are unlikely to invest in long-lived biomass when they cannot control its future use. Payments for carbon or biodiversity should be evaluated for transaction costs, permanence obligations and whether they inadvertently discourage adaptive pruning.

A longer-term priority is development of decision-support systems that combine climate zoning, farm resource constraints and shade-tree functional traits. Such systems should not produce a single optimised recipe. They should identify feasible portfolios and expose trade-offs: for example, which trees reduce heat most effectively, which increase drought competition, which provide marketable products, and how much carbon is sacrificed or gained under alternative pruning intensities. Validation should occur in farmer-managed conditions because model-optimal designs can fail when labour peaks, market access or tenure are ignored.

The ultimate research goal is therefore not to prove that cocoa agroforestry is universally superior. It is to identify where particular agroforestry designs expand the climatic and economic operating space of cocoa, where they merely redistribute trade-offs, and where climate exposure is severe enough that diversification or crop transition is more rational than continued investment in cocoa. The conditional adaptation effect reported by Wätzold *et al.* (2026) makes this boundary especially important. Research that defines limits to adaptation is as valuable as research that demonstrates benefits within those limits.

11. Conclusions

Cocoa agroforestry can contribute meaningfully to climate adaptation, carbon storage and biodiversity conservation, but its effectiveness depends on design and context rather than the presence of shade trees alone. The strongest evidence supports the capacity of trees to buffer radiation, temperature and atmospheric demand and to increase aboveground carbon and habitat complexity relative to simplified cocoa. Evidence for universal yield benefits, universal soil-fertility improvement, universal drought protection and universal pest suppression is substantially weaker. Extreme drought can reverse expected shade benefits when tree-crop competition for water becomes dominant, while excessive or poorly positioned crowns can reduce productive light and increase disease-conducive humidity.

The central management implication is to replace fixed shade prescriptions with climate-contingent functional shade design. Crown height, seasonal leaf phenology, rooting behaviour, litter traits, species identity, spatial arrangement and management through pruning determine whether facilitation exceeds competition. Elevated crowns and seasonally complementary species are promising design features, but their performance must be matched to local water balance, disease pressure, soils and farmer objectives. Carbon and biodiversity goals should be pursued without treating agroforests as substitutes for intact forests, and landscape planning must prevent cocoa expansion from converting high-carbon, high-biodiversity habitats.

Production decisions should also move beyond bean yield as the sole performance metric. Net income, labour demand, input costs, additional products, risk reduction and long-term stand persistence determine whether farmers can maintain diversified systems. Agroforestry that is technically sophisticated but economically or institutionally unmanageable is unlikely to remain complex after project support ends. The most credible pathway for cocoa in a warming world is therefore adaptive, place-specific agroforestry supported by secure tree rights, practical extension, viable markets and monitoring of both crop and ecosystem outcomes. In the most climatically exposed locations, even well-designed shade may not be sufficient, and resilience planning should include livelihood diversification and, where necessary, managed transition away from cocoa.

12. Limitations

As a critical narrative review, this synthesis is intrinsically exposed to selection and interpretive bias despite the use of a transparent search strategy, explicit eligibility criteria and structured appraisal. It did not apply a formal systematic-review protocol, calculate database-specific screening counts or perform a new quantitative meta-analysis. The evidence base is heterogeneous in study design, shade definitions, cocoa genotype, farm age, climate, soil and outcome measurement, which limits direct comparison and prevents derivation of a universal shade threshold. Long-term manipulative studies that jointly test climate, shade traits, yield, carbon, biodiversity and farm economics remain scarce, so some integrative conclusions necessarily depend on triangulation across separate studies. Geographic coverage is uneven, with substantial evidence from Ghana and selected sites in Latin America and Indonesia but less comparable long-term evidence from several other cocoa-producing countries. English-language accessibility may also have favoured internationally indexed literature. Finally, rapidly evolving research and changing climate conditions mean that the suitability of individual shade species and economic arrangements should be reassessed as new field evidence becomes available.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Author has declared that no competing interests exist.

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