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Research Article

Cocoa productivity-sustainability trade-off: A panel analysis of agricultural production system efficiency in West Africa

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Abstract This study investigates the productivity–sustainability trade-off in West African cocoa systems by examining how full-sun, partial-shade, smallholding, and agroforestry configurations balance yield performance with ecological integrity. Using a balanced panel dataset (1970–2020) from Cameroon, Côte d'Ivoire, Ghana, and Nigeria, system efficiencies were estimated through pooled regression models with robust standard errors, incorporating biophysical factors, market signals, and system-type interactions. Results show a clear productivity gradient in which full-sun systems achieve the highest yields, while agroforestry incurs the greatest output penalty, particularly in Cameroon. Ghana's partial-shade systems strike a more favourable balance between productivity and ecological preservation, whereas Nigeria's smallholdings perform well but remain structurally inefficient. Côte d'Ivoire's full-sun systems maintain high output at substantial environmental cost. The study concludes that ecological complexity reduces short-run yields but supports long-term resilience. It recommends tailored interventions, including ecosystem payments, regulated intensification, cooperative strengthening, and improved shade management.

Keywords: Productivity–sustainability trade-off, Cocoa production systems, Agroforestry, Panel data analysis, Production efficiency, Ecological integrity.

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Kakao verimliliği-sürdürülebilirlik dengesi: Batı Afrika'da tarımsal üretim sistemi verimliliğine ilişkin panel analizi

Özet Bu çalışma, Batı Afrika kakao sistemlerinde verimlilik-sürdürülebilirlik dengesini, tam güneş alan, kısmi gölge alan, küçük ölçekli ve tarımsal ormancılık konfigürasyonlarının verim performansı ile ekolojik bütünlüğü nasıl dengelediğini inceleyerek araştırmaktadır. Kamerun, Fildişi Sahili, Gana ve Nijerya'dan elde edilen dengeli bir panel veri seti (1970-2020) kullanılarak, biyofiziksel faktörler, piyasa sinyalleri ve sistem türü etkileşimlerini içeren sağlam standart hatalara sahip birleştirilmiş regresyon modelleri aracılığıyla sistem verimlilikleri tahmin edilmiştir. Sonuçlar, tam güneş alan sistemlerin en yüksek verimi elde ettiği, tarımsal ormancılığın ise özellikle Kamerun'da en büyük verim kaybına yol açtığı açık bir verimlilik eğilimi göstermektedir. Gana'nın kısmi gölge alan sistemleri verimlilik ve ekolojik koruma arasında daha elverişli bir denge kurarken, Nijerya'nın küçük ölçekli işletmeleri iyi performans gösterse de yapısal olarak verimsiz kalmaktadır. Fildişi Sahili'nin tam güneş alan sistemleri, önemli çevresel maliyetlerle yüksek verimi korumaktadır. Çalışma, ekolojik karmaşıklığın kısa vadeli verimi düşürdüğünü ancak uzun vadeli dayanıklılığı desteklediğini sonucuna varmıştır. Ekosistem ödemeleri, düzenlenmiş yoğunlaştırma, iş birliğinin güçlendirilmesi ve iyileştirilmiş gölge yönetimi de dahil olmak üzere özel müdahaleler önermektedir.

Anahtar Kelimeler Verimlilik-sürdürülebilirlik dengesi, Kakao üretim sistemleri, Tarımsal ormancılık, Panel veri analizi, Üretim verimliliği, Ekolojik bütünlük.

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1. INTRODUCTION

The specter of Malthus remains relevant as the global population approaches 10 billion, intensifying the demand for food and placing extraordinary pressure on agricultural systems. While technological advances and land expansion since the 18th century have enabled food production to outpace population growth, these gains have come at significant ecological costs (Ramankutty et al., 2018), including biodiversity loss (Zhang et al., 2020), soil degradation (Kopittke et al., 2019), and water pollution, problems closely linked to the high-input, monoculture practices of the Green Revolution (Foley et al., 2011). Despite these challenges, research highlights that alternative management strategies, such as closing yield gaps on underperforming lands, increasing cropping efficiency, diversifying crops, and reducing waste, can help double food production (Zhang et al., 2020), while shrinking agriculture's environmental footprint (Wijerathna-Yapa & Pathirana, 2022; Foley et al., 2011). The intellectual legacies of Elinor Ostrom and Theodore Schultz are echoed in calls for more adaptive, participatory, and ecologically informed approaches to managing agricultural commons and recognizing farmers' capacity for innovation (Nordman, 2021; Ostrom, 2015; Robertson & Swinton, 2005; Schultz, 1993). Ultimately, a transformation toward sustainable, climate-smart, and biodiversity-friendly agricultural systems is essential to reconcile food security with environmental integrity in the face of ongoing population growth (WijerathnaYapa & Pathirana, 2022).

West Africa presents a natural laboratory. According to Dago et al. (2025), Asante et al. (2025) and Michel et al. (2024), distinct national agricultural production identities have emerged: Côte d'Ivoire's full-sun cocoa and intensive systems, Ghana's partial-shade cultivation, Nigeria's fragmented smallholdings, and Cameroon's complex agroforestry. We lack, however, a rigorous, comparative quantification of the production opportunity cost of these more sustainable practices. Without this knowledge, policymakers are left to choose between the Scylla of food insecurity and the Charybdis of environmental collapse. Consequently, this study aims to empirically test the hypothesized trade-offs along the production–sustainability frontier by quantifying and comparing the productivity differentials and economic implications across these four dominant cocoa production systems.

The full-sun system is a high-input monoculture designed to maximize short-term yield through mechanization and chemical inputs. However, this focus on productivity comes at a substantial ecological cost, as it is strongly associated with reduced biodiversity, lower carbon sequestration, and increased vulnerability to pests, diseases, and climate shocks, often accelerating soil degradation and pollution. In contrast, the partial-shade system provides a more balanced intermediate approach. By maintaining a defined canopy cover, it offers critical microclimate buffering and improves soil health and pest regulation without necessarily sacrificing yield, though its success depends on achieving a crop-specific, optimal shade level to avoid diminishing returns.

Meanwhile, the smallholding system represents the highly adaptable, family-run farms that dominate global production. Their management strategies are diverse, shaped by local constraints, but when they adopt ecological practices like diversification, they can significantly enhance nutrient efficiency, soil organic matter, and long-term resilience. The most ecologically integrated model is the agroforestry system, which intentionally layers trees with crops or livestock. This design delivers a suite of ecosystem services, from carbon storage and microclimate regulation to improved soil fertility and pest control, often matching the long-term economic viability of sun monocultures for smallholders, provided shade is actively managed to balance productivity with ecological benefits.

The existing literature describes distinct national cocoa production systems in West Africa but lacks a rigorous, comparative quantification of their associated production opportunity costs. This study aims to fill this gap by empirically measuring the trade-offs along the production–sustainability frontier to provide an evidence base for differentiating policy across these systems.

Theoretical and conceptual framework

Recent research extends the traditional agricultural production function by integrating ecological sustainability and system-level management, conceptualizing a "Production-Sustainability Frontier" that captures the trade-offs and synergies between maximizing cocoa output and maintaining ecological health (Yang et al., 2024). Song et al., (2022) and Wittwer et al., (2021) emphasize that sustainable agriculture requires recognizing the multifunctionality of agricultural systems, where cocoa production, ecological regulation, and social functions interact and sometimes conflict, necessitating multi-objective management and policy interventions tailored to local conditions. Similarly, the works of Dietrich et al. (2025), Wittwer et al., (2021) and Pretty (2018) have shown that incorporating ecosystem services, such as biodiversity, soil fertility, and water regulation, into production models reveals that practices like organic and conservation agriculture can enhance ecosystem multifunctionality, supporting both yields and environmental outcomes, though conventional systems may still deliver the highest yields at the cost of reduced sustainability.

Innovative frameworks and management strategies, such as integrated nutrient management, conservation agriculture, and functional ecological selection, are highlighted as pathways to optimize both productivity and sustainability, moving agricultural systems along the ProductionSustainability Frontier (Brooker et al., 2021; Shah & Wu, 2019; Pretty, 2018). Economic and ecological models now increasingly account for the substitutability between ecosystem services and conventional inputs, underlining the need for comprehensive indicators to guide decisionmaking (Dietrich et al., 2025). Yang et al. (2024), Pretty, (2018), and Robertson et al. (2014) posit that the transition toward sustainable intensification and functional ecosystem management is essential for meeting global food demands while minimizing environmental degradation, with success depending on adaptive management, policy support, and collaboration across disciplines and stakeholders.

Aim of the study

The aim of the study is to examine the trade-offs between ecological sustainability and cocoa production efficiency across different farming systems, assessing how system design, scale, and adaptive responses to market signals influence productivity outcomes.

2. MATERIAL AND METHOD

Data and sampling method

We constructed a balanced panel dataset from 1970 to 2020 for four countries: Cameroon, Côte d'Ivoire, Ghana, and Nigeria. Data on cocoa production, harvested area, and producer value were sourced from FAOSTAT and national statistical agencies. The literature is replete with the evidence that Côte d'Ivoire's agricultural production sector is dominated by full-sun, high-input monoculture systems focused on maximizing yield, primarily located in the humid forest belt (Obahoundjé et al., 2025; Dago & Pei 2025; Schroth et al., 2016). Dago & Pei (2025) find that these systems are highly sensitive to temperature increases and soil moisture deficits, with recent research highlighting significant yield reductions (2.5% to 37%) during dry years due to water stress and high evapotranspiration, making them particularly vulnerable to climate variability and drought. Bunn et al. (2019) and Wessel et al. (2015) posit that Ghana employs more partial-shade systems, where cocoa is intercropped with retained forest trees, especially in the deciduous forest zone. This approach offers moderate resilience to climate stress, but the region remains vulnerable to intense dry spells and rainfall variability, with projections indicating a reduction in suitable cocoa-growing areas in the north and increased climatic uncertainty in central regions (Asante et al., 2025).

Asante et al. (2025) and Schroth et al. (2016) describes that Nigeria's cocoa production is characterized by diverse smallholdings and mixed food-cocoa systems in rainforest and derived savanna zones, resulting in varied adaptive capacities but high exposure to land degradation and erratic rainfall patterns. Michel et al. (2024) and Ariza-Salamanca et al. (2023) note that Cameroon stands out for its complex agroforestry systems, where cocoa is grown with native trees in a bimodal rainforest climate, providing the highest inherent resilience among the four countries; however, these systems are still susceptible to long-term climate shifts and require adaptation in shade tree species composition to maintain productivity under future conditions. Across all countries, adaptation strategies such as increased use of shade trees, agroforestry, and site-specific management are recommended to mitigate climate risks and sustain cocoa production (Michel et al., 2024; Bunn et al., 2019)

Statistical analysis

After rigorous diagnostic testing (Hausman, Breusch-Pagan, VIF), the study rejected both fixed and random effects in favour of a Pooled OLS model with robust standard errors, specified as follows:

$\Delta Productionit=\beta 0+\beta 1\Delta HarvestedAreait+\mathrm{L}.\beta 2\Delta Valueit-1+\beta 3HA\_CamSysi+\beta 4HA\_GhanaSysi+\beta 5$
$HANigSys+\epsilon it$……………………………………………………………………………(1)

$\Delta Yieldit=\beta 0+\beta 1\Delta HarvestedAreait+\mathrm{L}.\beta 2\Delta Valueit-1+\beta 3HA\_CamSysi+\beta 4HA\_GhanaSysi+\beta 5$
$HANigSysi+\epsilon it$

……………………………………………………………………………………………….(2)

Where:

i. ΔProductionit is the first-differenced cocoa production in country$_i$, year$_t$.

ii. ΔYieldit is the first-differenced cocoa Yield in country$_i$, year$_t$.

iii. ΔHarvestedAreait is the change in harvested area.

iv. ΔValueit−1 is the lagged change in producer value. (Gross Production Value (constant 2014-2016 thousand US$))

v. *CamSysi*, *GhanaSysi NigSysi* are the dominant cocoa production system dummies for each of Cameroon, Ghana and Nigeria respectively. They are time-invariant, with Côte d'Ivoire's full-sun system as the reference category.

vi. HA_CamSysi is the interaction between harvested area (D_Harvested_scaled) and CamSysi

vii. HA_GhanaSysi is the interaction between harvested area (D_Harvested_scaled) and GhanaSysi
viii. HA_NigSysi is the interaction between harvested area (D_Harvested_scaled) and NigSysi

This dynamic specification in differences controls for unobserved time-invariant country characteristics and models the lagged response to economic signals.

3. RESULTS

Descriptive statistics

Country level statistics

Descriptive statistics reveal distinct structural and performance profiles across the four major cocoa-producing nations, delineating clear institutional and technological paradigms (Table 1). Côte d'Ivoire exhibits a pronounced productivity constraint, with an average yield of 0.35 tons per hectare resulting in an output of 169,312 tons from 468,844 hectares. This extensive, low-yield model is indicative of a systemic low-technology equilibrium, commonly associated with constraints in access to improved inputs, aging tree stock, and underdeveloped credit and extension systems. In stark contrast, Ghana operates at the regional efficiency frontier, achieving a yield of 0.539 t/ha. This high productivity, generating 1.04 million tons from 1.89 million hectares, reflects a coordinated, institutionally-driven model typified by centralized quality control and input distribution. However, this system demonstrates significant output volatility (standard deviation equal to 59% of the mean), highlighting underlying exposure to climatic and market shocks.

Nigeria presents a salient case of scale without commensurate efficiency. While possessing the second-largest harvested area (1.30 million hectares), its average yield of 0.361 t/ha is substantially lower, producing only 488,018 tons. This sizable productivity gap, where the country utilizes 69% of Ghana's land area to produce less than half of its output, points to profound coordination failures within a fragmented policy and institutional landscape. Conversely, Cameroon's profile suggests a deliberate, resilience-oriented strategy. With a modest but stable yield of 0.314 t/ha from 887,321 hectares, yielding 278,569 tons, the sector demonstrates the lowest relative production volatility (32% of the mean). This pattern aligns with an agroforestry-based production system that trades maximum potential yield for risk mitigation, biodiversity conservation, and long-term ecological sustainability.

Collectively, the statistics underscore that national cocoa sectors are defined not merely by biophysical endowments but by their underlying institutional architectures. The data delineate a clear hierarchy, from Ghana's high-efficiency, coordinated system and Côte d'Ivoire's extensive, input-constrained model to Nigeria's inefficient, fragmented sector and Cameroon's stable, agroecological approach. These divergent profiles frame the core analytical challenge: understanding how specific institutional configurations either facilitate or hinder the translation of land and labor into sustainable productivity and economic value.

Table 1. Descriptive statistics of variables of interest by country

-> Country_ID	=	1(Côte-d'Ivoire)			
Variable	Obs	Mean	Std. dev.	Min	Max
Production (tons)	53	169312.3	76494.2	82500	344752
Yield (tons/ha)	53	.3495245	.0778573	.202	.6618
Value (USD)	53	249146	112562.5	121400	507309
Areaharves~d (ha)	53	468843.8	127184	322521	771917
-> Country_ID	=	2 (Ghana)			
Variable	Obs	Mean	Std. dev.	Min	Max
Production (tons)	53	1041011	619098.2	179156	2358991
Yield (tons/ha)	53	.5393981	.0734388	.3782	.7006
Value (USD)	53	1531866	911013.6	263631	3471296
Areaharves~d (ha)	53	1894745	1155143	404300	4716003
-> Country_ID	=	3 (Nigeria)			
Variable	Obs	Mean	Std. dev.	Min	Max
Production (tons)	53	488018.1	250055.3	166700	1047385
Yield (tons/ha)	53	.3612245	.1107644	.2054	.5604
Value ((USD)	53	718127.1	367960.7	245302	1541245
Areaharves~d (ha)	53	1301364	378217.8	686531	2000000
-> Country_ID	=	4 (Cameroon)			
Variable	Obs	Mean	Std. dev.	Min	Max
Production (tons)	53	278569.3	87976.13	140000	485000
Yield (tons/ha)	53	.3140321	.0712747	.2	.498
Value (USD)	53	409919.5	129458.3	206012	713686
Areaharves~d (ha)	53	887320.7	222804.7	700000	1359550

Source: Author's Computation, 2025

Pooled statistics

Table 2 (N = 212) shows a dataset with large scale and high dispersion in the quantity and value measures, but comparatively stable yields. Mean production is 494,228 with a standard deviation of

475,946 (min = 82,500; max = 2,358,991), implying nearly one-to-one variability (CV ≈ 0.96) and pronounced right-skew, a few very large observations drive much of the mass. Value follows the same pattern (mean = 727,265, SD = 700,362, CV ≈ 0.96), indicating that monetary outcomes mirror output volatility. Area harvested averages 1,138,068 (SD = 811,865, CV ≈ 0.71), showing large but somewhat lower relative dispersion than production and value. By contrast, yield is much less variable (mean = 0.391, SD = 0.122, CV ≈ 0.31; range 0.20–0.7006), suggesting that perhectare productivity is relatively stable across observations even when total output and area fluctuate dramatically.

Therefore, the high heteroskedasticity and skew in production, value and area argue for the rescaling of the variables. This study employs per-hectare yield as its primary metric to isolate productivity dynamics from mere scale effects. The selection of yield is further justified by its relatively stable variability, which provides a more robust dependent variable for isolating the impacts of technological adoption and system-level management. Conversely, total production volume is reserved for analyses where scale economies and market-level impacts are the central objects of inquiry, a distinction that underpins the analytical framework of this research.

Table 2. Descriptive statistics of variables of interest

Variable	Obs	Mean	Std. dev.	Min	Max
Production	212	494227.7	475945.6	82500	2358991
Yield	212	.3910448	.1215442	.2	.7006
Value	212	727264.6	700362.1	121400	3471296
Areaharves~d	212	1138068	811865.4	322521	4716003

Source: Author's Computation, 2025

Regression results

Primary determinants of production

Table 3 presents the regression results for the determinants of annual changes in cocoa production. The most substantial driver is the scaled harvested area variable. A one-standard-deviation increase in the scaled harvested area is associated with an increase in production of approximately 484.21 tons (β = 484.21, SE = 36.87, t = 13.13, p < 0.001; 95% CI: 411.51 to 556.91 tons). This confirms that land expansion remains the primary short-run lever for output growth.

The lagged change in production value shows a significant negative relationship (β = -0.112, SE = 0.046, t = -2.44, p = 0.015). This suggests an inverse short-run adjustment: higher value in the preceding year is associated with a subsequent production decrease, which may reflect market-driven cyclicality or a post-surplus normalization.

Production system dummy variables, benchmarked against the intensive full-sun system of Côte d'Ivoire, reveal significant structural penalties. Cameroon's agroforestry system shows the largest negative coefficient, associated with an estimated production reduction of 449.80 tons (SE = 83.34, p < 0.001). Nigeria's smallholder system also shows a significant negative effect (-370.99 tons, SE = 147.16, p = 0.012). The coefficient for Ghana's partial-shade system is negative but not statistically significant at conventional levels (-100.38 tons, SE = 59.34, p = 0.092).

Collectively, the model supports a clear intensification-sustainability trade-off. Area expansion and intensive monoculture systems are associated with higher production, while more diversified and shade-based systems correlate with lower output, potentially reflecting a trade-off for ecological or risk-mitigation benefits.

Table 3. Determinants of annual cocoa production changes (tons)

Variable	Coefficient	Robust Std. Error	tstatistic	pvalue	95% Confidence Interval	
					Lower Bound	Upper Bound
D_Harvested_scaled	484.209***	36.868	13.13	0.000	411.505	556.913
L.D_Value	-0.11**	0.046	-2.44	0.015	-0.203	-0.022
HA_CamSys	-449.80***	83.343	-5.40	0.000	-614.159	-285.449
HA_GhanaSys	-100.38	59.339	-1.69	0.092	-217.397	16.638
HA_NigSys	-370.99**	147.158	-2.52	0.012	-661.193	-80.795
Constant	4,774.25	3,467.308	1.38	0.170	-2,063.343	11,611.840

Source: Author's Computation; * ***, **, * indicate significance at 1%, 5%, and 10% levels, respectively. Reference category for system dummies is Full-Sun Intensive (Côte d'Ivoire).

Model statistics on determinants of cocoa production changes

Table 4 reveals the model statistics (cocoa production change). The model demonstrates strong explanatory power and statistical reliability. The highly significant F-statistic of 57.70 (p<0.000) confirms the model's overall validity, rejecting the null hypothesis that all coefficients are zero. With an R-squared of 0.607, the explanatory variables account for approximately 61% of the variation in the dependent variable, representing substantial predictive capacity for social science research. The Root MSE of 51,497 provides the average magnitude of prediction errors, which must be evaluated relative to the scale of the outcome variable. These diagnostics collectively indicate a robust, well-specified model that reliably captures systematic relationships within the data.

Table 4. Model statistics (cocoa production changes)

Statistic	Value
Number of Observations	204
F-statistic	57.70
Prob > F	0.0000
R-squared	0.6073
Root MSE (Tons)	51,497

Source: Author's Computation, 2025

Variance Inflation Factor (VIF) diagnostics on determinants of cocoa production changes

The VIF diagnostics presented in Table 5 indicate no meaningful multicollinearity concerns in the model. According to Akinwande et al. (2015), a suppressor, and, by implication, any predictor, should only be retained in a model if its VIF is below 5, which they propose as a practical threshold for acceptable multicollinearity. All variance inflation factors in this model fall well below this conservative threshold, with a mean VIF of 1.50 confirming minimal correlation among predictors. The highest VIF of 2.25 for harvested area suggests it shares only moderate variance with other variables, while the near-unity VIFs for lagged value (1.03) and the Cameroon system (1.10) demonstrate their essential statistical independence. These results validate the model's specification and ensure the stability and reliability of the coefficient estimates.

Table 5. Variance Inflation Factor (VIF) diagnostics (cocoa production)

Variable	VIF	1/VIF
D_Harvested_scaled (tons)	2.25	0.445
HA_GhanaSys	1.96	0.509
HA_NigSys	1.17	0.856
HA_CamSys	1.10	0.906
L.D_Value (USD)	1.03	0.973
Mean VIF	1.50	

Source: Author's Computation, 2025

Determinants of cocoa yield changes

Table 6 presents the determinants of annual changes in cocoa yield (measured in tons per hectare, t/ha). The model explains a substantial proportion of yield variation ($R^2 = 0.795$). The results highlight a core intensification-extensification dynamic: increasing total production is associated with higher yields, while expanding harvested area is linked to lower yields. Specifically, a 1,000-ton increase in annual cocoa production corresponds to a yield increase of 0.000782 t/ha (β = 7.82e-07, $p < 0.001$). Conversely, a 1,000-hectare expansion in harvested area corresponds to a yield decrease of 0.000409 t/ha (β = -4.09e-07, $p < 0.001$). This indicates that productivity gains stem from intensification within existing cultivated areas, whereas extensification may involve cultivating marginal lands or inefficient resource allocation.

Analysis of production system dummy variables, with Côte d'Ivoire's full-sun system as the benchmark, reveals distinct yield effects. Nigeria's smallholder system shows the strongest positive association with yield change (0.000154 t/ha, $p < 0.001$), followed by Ghana's partial-shade system (0.000081 t/ha, $p = 0.014$). Cameroon's agroforestry system shows a significant negative coefficient (-0.000312 t/ha, $p = 0.002$), confirming a yield trade-off for its ecological structure. The lagged change in production value shows no significant effect ($p = 0.284$), suggesting yield changes in the short run are driven more by technical and managerial factors than by prior price signals.

Collectively, these findings underscore that strategies to enhance cocoa yields should prioritize improving production efficiency on current lands over expanding cultivation into new areas, which may diminish average productivity.

Table 6. Determinants of agricultural yield changes (tons/ha)

Variable	Coefficient	Robust Std. Error	tstatistic	pvalue	95% Confidence Interval	
					Lower Bound	Upper Bound
L.D_Value	1.70e-08	1.58e-08	1.07	0.284	-1.42e-08	4.81e-08
HA_CamSys	-0.00031***	0.000100	-3.12	0.002	-0.000509	-0.000115
HA_GhanaSys	0.00008**	0.000033	2.48	0.014	0.000017	0.000146
HA_NigSys	0.00015***	0.000035	4.43	0.000	0.000085	0.000222
Harvested Area	-4.09e-07***	3.60e-08	-11.36	0.000	-4.80e-07	-3.38e-07
Production	7.82e-07***	6.41e-08	12.20	0.000	6.56e-07	9.09e-07
Constant	0.00051	0.001763	0.29	0.772	-0.002967	0.003988

Source: Author's Computation, 2025. * ***, **, * indicate significance at 1%, 5%, and 10% levels, respectively. Reference category for system dummies is Full-Sun Intensive (Côte d'Ivoire).

Model statistics on determinants of cocoa yield changes

Tale 7 reveals the model statistics (cocoa yield changes). The model demonstrates statistical robustness and substantive explanatory power. With an F-statistic of 36.25 ($p<0.000$), the model overwhelmingly rejects the null hypothesis, confirming that the collective explanatory capacity is non-random and theoretically meaningful. The R-squared value of 0.795 represents a remarkable achievement in agricultural economics, indicating that nearly 80% of the variance in cocoa yield changes is systematically explained by the specified determinants.

The Root Mean Square Error of 0.024 is contextualized against the scale of yield measurements, this represents a high degree of predictive precision given the dependent variable's metric. The sample size of 204 observations provides substantial statistical power while maintaining analytical rigor through first-differencing to address temporal dependencies.

These diagnostics collectively affirm that the model is well-specified, statistically reliable, and substantively significant, providing a robust foundation for policy inference and theoretical advancement in understanding cocoa yield determinants across different production systems.

Table 7. Model statistics (cocoa yield changes)

Statistic	Value
Number of Observations	204
F-statistic	36.25
Probability > F	0.000
R-squared	0.795
Root Mean Square Error	0.024

Source: Author's Computation, 2025. Note: * ***, **, * indicate significance at 1%, 5%, and 10% levels, respectively. Reference category for system dummies is Full-Sun Intensive (Côte d'Ivoire). All variables are first-differenced.

3.2.6 Variance Inflation Factor (VIF) Diagnostics on Determinants of Cocoa Yield Changes The VIF diagnostics (cocoa yield changes) are contained in Table 8. The VIF indicate acceptable levels of multicollinearity with no concerning statistical interference. The mean VIF of 2.04 falls well below the conservative threshold of 5, confirming that coefficient estimates remain stable and reliable. While harvested area shows moderate correlation with other predictors (VIF = 4.18), this is expected given the natural relationship between area and production in agricultural systems and does not approach levels that would compromise inference. All other variables demonstrate excellent statistical independence, with VIF values clustering near 1, particularly the lagged value variable (1.09) and Cameroon system dummy (1.18). These results validate the model's specification and ensure that the significant relationships identified represent genuine effects rather than statistical artifacts.

Table 8. Variance Inflation Factor (VIF) diagnostics (cocoa yield changes)

Variable	VIF	1/VIF
D_Harveste~a	4.18	0.239050
D_Production	2.55	0.392674
HA_GhanaSys	2.00	0.499993
HA_NigSys	1.26	0.795259
HA_CamSys	1.18	0.845245
D_Value		
L1.	1.09	0.917890
Mean VIF	2.04	

Source: Author's Computation, 2025

4. DISCUSSION

This study empirically quantifies the location of four West African cocoa production systems along the Production–Sustainability Frontier, providing a cross-national, evidence-based framework for understanding their relative performance and trade-offs. The findings robustly support the conceptual theory positing that agricultural systems operate within a quantifiable space between maximizing output and maintaining ecological functions (Yang et al., 2024; Dietrich et al., 2025). By placing the systems of Côte d'Ivoire, Ghana, Nigeria, and Cameroon on a common frontier, this analysis advances beyond country-specific or static comparisons prevalent in the literature, directly addressing a critical research gap (Binam et al., 2008; Niether et al., 2020).

Validating system-specific trade-offs and hierarchies

The clear hierarchy of production coefficients, Full-Sun > Partial-Shade > Smallholding > Agroforestry, validates and quantifies the well-documented trade-off between yield and ecological integration. The substantial penalty for Cameroon's agroforestry (β = −449.80) aligns with meta-analytic findings that agroforestry yields are approximately 25% lower than monocultures (Niether et al., 2020). This quantifies the "production opportunity cost" of such systems, a gap explicitly noted in the literature (Konaté et al., 2025). Conversely, Ghana's marginal penalty (β = −100.38, p = 0.092) confirms that partial-shade systems can achieve near-competitive yields, corroborating the "sustainable intensification" model where moderate canopy cover offers microclimate benefits without drastic yield sacrifice (Sonwa et al., 2018). This result offers a crucial empirical counterpoint to the dichotomy often presented between high-yield and high-sustainability systems.

The intensification-extensification dichotomy and yield gaps

A core contribution of this study is its evidence that productivity gains are driven by intensification, not extensification. The negative coefficient for harvested area on yield (β = -4.09e-07) and the positive coefficient for production on yield (β = 7.82e-07) provide a powerful economic argument against land expansion as a growth strategy. This directly reinforces yield gap literature which asserts that the greatest potential for increasing output lies in closing management gaps on existing farms through improved agronomy, pest control, and input use, not in cultivating new, often marginal, land (Asante et al., 2022; Kongor et al., 2018). Our findings suggest that policies promoting area expansion may inadvertently lower sector-wide productivity, a critical insight for national agricultural strategies.

Structural vs. ecological constraints: the cases of Nigeria and Cameroon

The analysis dissects the distinct sources of constraint within the frontier. Nigeria’s significant negative production coefficient, coupled with its strong positive yield effect, reveals a system limited by structural inefficiency, not ecological choice. The high yield dispersion and low aggregate efficiency mirror studies highlighting the crippling effect of transaction costs, poor extension, and fragmented smallholdings (Binam et al., 2008; Adegbite & Machethe, 2020). This system is trapped not by the shade-yield trade-off but by institutional failures that prevent the realization of its latent intensification potential.

In contrast, Cameroon’s results epitomize a deliberate ecological optimization. Its pronounced production penalty reflects a strategic choice to prioritize long-term resilience, carbon storage, and biodiversity, benefits documented in agroforestry research (Franzen & Borgerhoff Mulder, 2007; Niether et al., 2020). The stability of its production (lowest relative volatility) underscores the risk-mitigation value of complex agroforestry, a feature increasingly vital under climate change (Schroth et al., 2016).

Market signals and adaptive management

The significant negative lagged value coefficient (β = −0.112) confirms that production decisions are dynamically adaptive to prior price signals. This aligns with economic models of agricultural supply but highlights a volatility loop where high prices lead to subsequent contractions, potentially destabilizing markets and incomes. However, the finding that yields themselves are price-insensitive (p = 0.284) is pivotal. It decouples short-term production decisions from long-term land productivity, indicating that yield improvements depend on technical and managerial factors, access to inputs, knowledge, and credit, not on market timing. This challenges the efficacy of price signals alone as levers for sustainable intensification and underscores the importance of robust extension systems, as identified in efficiency studies (Binam et al., 2008).

Policy implications: A differentiated pathway

The empirical frontier mandates differentiated, system-specific policies:

i. Ghana (Partial-Shade): Policy should focus on targeted sustainable intensification within the shaded canopy. Strengthening extension for integrated soil fertility and shade management (Asante et al., 2021) can further narrow yield gaps while preserving the documented ecological co-benefits and carbon storage (Niether et al., 2020).

ii. Nigeria (Smallholding): The imperative is structural transformation. Policy must address coordination failures through land consolidation incentives, cooperative development, and digital market platforms to unlock economies of scale and enable the efficient use of yield-enhancing technologies.

iii. Cameroon (Agroforestry): The pathway requires monetizing the sustainability premium. Developing Payments for Ecosystem Services (PES), carbon credit mechanisms, and premium markets for biodiverse cocoa is essential to compensate for the quantified yield penalty and make ecological farming economically competitive (Wainaina et al., 2021).

iv. Côte d'Ivoire (Full-Sun): Policy must shift towards regulated intensification. This involves enforcing deforestation moratoriums, regulating agrochemical use to mitigate pollution and health risks (Bandanaa et al., 2024), and incentivizing intercropping to reduce systemic vulnerability.

Synthesis

Collectively, these findings confirm that agricultural performance in West Africa is not a linear function of intensification but a multidimensional optimization problem along the Production– Sustainability Frontier. The yield model powerfully illustrates one axis of this frontier: the tradeoff where intensification boosts yields but extensification diminishes them, a dynamic that varies significantly by system. The econometric evidence provides quantitative anchors for a new generation of policies, those that simultaneously internalize ecosystem values, incentivize adaptive management, and acknowledge the differentiated realities of production systems. The study advances agricultural economic theory by empirically demonstrating how ecological integration, scale, and adaptive decision-making co-determine productivity, positioning sustainable intensification not as a trade-off but as a recalibration of production logic within planetary limits.

Limitations of the study

This study has several inherent limitations that constrain the scope of its conclusions while delineating clear pathways for future inquiry. First, the reliance on aggregated national statistics (FAOSTAT) masks critical sub-national heterogeneity in agro-ecological conditions and farm management, and the classification of countries into singular system types simplifies on-farm diversity. Second, the "sustainability" dimension is inferred indirectly from system type and associated yield penalties, lacking direct empirical measurement of environmental indicators like soil carbon or biodiversity, which limits a full cost-benefit assessment. Third, the economic modeling uses highly aggregated proxies for market signals, omitting nuanced socio-economic drivers such as credit access, tenure security, and institutional support that shape farmer decisions. Finally, the econometric approach captures short-run dynamics effectively but may not account for long-term ecological trends or path dependencies. These limitations do not undermine the core findings but underscore the need for integrated, farm-level research linking specific management practices to multidimensional sustainability outcomes.

5. CONCLUSION

This study maps West Africa's cocoa systems along an empirically quantified production–sustainability frontier, revealing a stark trade-off gradient. Côte d'Ivoire's intensive full-sun model maximizes output but at high ecological cost; Ghana's partial-shade systems offer a balanced compromise with stable yields; Nigeria's smallholders show strong intensification potential hamstrung by structural inefficiency; and Cameroon's agroforestry systems deliberately exchange yield for long-term resilience. There is no single "best" system, only context-appropriate pathways. Sustainable cocoa futures depend not on a universal blueprint, but on policies tailored to each system's distinct logic, constraints, and ecological footprint. The future of chocolate lies in differentiated strategies, not a one-size-fits-all solution.

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Contribution Rate Statement Summary of Researchers

This is a single author paper; it requires no other consent to publish other than me.

Conflict of Interest

Author has no conflict/competing interests to declare

REFERENCES

Abdulkarim, Y. (2023). A systematic review of investment indicators and economic growth in Nigeria. *Humanities and Social Sciences Communications*, *10*, 1–13. https://doi.org/10.1057/s41599-023-02009-x

Adegbite, O., & Machethe, C. (2020). Bridging the financial inclusion gender gap in smallholder agriculture in Nigeria: An untapped potential for sustainable development. *World Development*, *125*, 104755. https://doi.org/10.1016/j.worlddev.2019.104755

Akinwande, M., Dikko, H., & Samson, A. (2015). Variance Inflation Factor: As a condition for the inclusion of suppressor variable(s) in regression analysis. *Open Journal of Statistics*, *5*(7), 754–767. https://doi.org/10.4236/ojs.2015.57075

Anjos, A. J., & Chaves, C. S. (2021). Características do componente forrageiro em sistemas silvipastoris. *Scientific Electronic Archives*, *14*(3), 39–48. https://doi.org/10.36560/14320211239

Ariza-Salamanca, A. J., Navarro-Cerrillo, R., Quero-Pérez, J. L., Gallardo-Armas, B., Crozier, J., Stirling, C., de Sousa, K., & González-Moreno, P. (2023). Vulnerability of cocoa-based agroforestry systems to climate change in West Africa. *Scientific Reports*, *13*(1), 37180. https://doi.org/10.1038/s41598-023-37180-3

Asante, P. A., Rahn, E., Anten, N. P. R., Zuidema, P. A., Morales, A., & Rozendaal, D. (2025). Climate change impacts on cocoa production in the major producing countries of West and Central Africa by mid-century. *Agricultural and Forest Meteorology*, *350*, 110393. https://doi.org/10.1016/j.agrformet.2025.110393

Asante, P. A., Rahn, E., Zuidema, P., Rozendaal, D., van der Baan, M. E. G., Läderach, P., Asare, R., Cryer, N., & Anten, N. (2022). The cocoa yield gap in Ghana: A quantification and an analysis of factors that could narrow the gap. *Agricultural Systems*, *203*, 103473. https://doi.org/10.1016/j.agsy.2022.103473

Asante, P. A., Rozendaal, D., Rahn, E., Zuidema, P., Quaye, A., Asare, R., Läderach, P., & Anten, N. (2021). Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana. *Agricultural Systems*, *197*, 103214. https://doi.org/10.1016/j.agsy.2021.103214

Bandanaa, J., Asante, I. K., Annang, T. Y., Blockeel, J., Heidenreich, A., Kadzere, I., Schader, C., & Egyir, I. (2025). Social and environmental trade-offs and synergies in cocoa production: Does the farming system matter? *Sustainability*, *17*(4), 1674. https://doi.org/10.3390/su17041674

Bandanaa, J., Asante, I. K., Egyir, I., Annang, T. Y., Blockeel, J., Heidenreich, A., Kadzere, I., & Schader, C. (2024). Trade-offs and synergies between economic and environmental cocoa farm management decisions. *Global Challenges*, *8*, 202400041. https://doi.org/10.1002/gch2.202400041

Binam, J. N., Gockowski, J., & Nkamleu, G. B. (2008). Technical efficiency and productivity potential of cocoa farmers in West African countries. *The Developing Economies*, *46*(3), 242–263. https://doi.org/10.1111/j.1746-1049.2008.00065.x

Black, E., Pinnington, E., Wainwright, C. M., Lahive, F., Quaife, T., Allan, R., Cook, P., Daymond, A., Hadley, P., McGuire, P., Verhoef, A., & Vidale, P. L. (2020). Cocoa plant productivity in West Africa under climate change: A modelling and experimental study. *Environmental Research Letters*, *15*(10), 1040b4. https://doi.org/10.1088/1748-9326/abc3f3

Brooker, R., George, T., Homulle, Z., Karley, A., Newton, A., Pakeman, R., & Schöb, C. (2021). Facilitation and biodiversity–ecosystem function relationships in crop production systems and their role in sustainable farming. *Journal of Ecology*, *109*(5), 2054–2067. https://doi.org/10.1111/1365-2745.13592

Bunn, C., Läderach, P., Quaye, A., Muilerman, S., Noponen, M., & Lundy, M. (2019). Recommendation domains to scale out climate change adaptation in cocoa production in Ghana. *Climate Services*, *16*, 100123. https://doi.org/10.1016/j.cliser.2019.100123

Cerda, R., Allinne, C., Gary, C., Tixier, P., Harvey, C., Krolczyk, L., Mathiot, C., Clément, E., Aubertot, J., & Avelino, J. (2017). Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. *European Journal of Agronomy*, *82*, 308–319. https://doi.org/10.1016/j.eja.2016.09.019

Clough, Y., Krishna, V., Corre, M. D., Darras, K., Denmead, L. H., Meijide, A., Moser, S., Musshoff, O., Steinebach, S., Veldkamp, E., Allen, K., Barnes, A. D., Breidenbach, N., Brose, U., Buchori, D., Daniel, R., Finkeldey, R., Harahap, I., Hertel, D., ... Scheu, S. (2016). Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. *Nature Communications*, *7*(1), 13137. https://doi.org/10.1038/ncomms13137

Dago, D. A., & Pei, Y. (2025). Evaluating the position of Côte d'Ivoire's cocoa industry on the global production chain and the influencing factors. *Sustainability*, *17*(3), 1013. https://doi.org/10.3390/su17031013

Dietrich, A., Carini, V., Vico, G., Bommarco, R., & Hansson, H. (2025). Changing the understanding of crop production: Integrating ecosystem services into the production function. *Ecological Economics, 226*, 108526. https://doi.org/10.1016/j.ecolecon.2025.108526

Drinkwater, L. E., & Snapp, S. S. (2022). Advancing the science and practice of ecological nutrient management for smallholder farmers. *Frontiers in Sustainable Food Systems*, *6*, 921216. https://doi.org/10.3389/fsufs.2022.921216

Durand-Bessart, C., Tixier, P., Quinteros, A., Andreotti, F., Rapidel, B., Tauvel, C., & Allinne, C. (2020). Analysis of interactions amongst shade trees, coffee foliar diseases and coffee yield in multistrata agroforestry systems. *Crop Protection, 132*, 105137. https://doi.org/10.1016/j.cropro.2020.105137

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature, 478*(7369), 337–342. https://doi.org/10.1038/nature10452

Franzen, M., & Borgerhoff Mulder, M. (2007). Ecological, economic and social perspectives on cocoa production worldwide. *Biodiversity and Conservation, 16*(13), 3835–3849. https://doi.org/10.1007/s10531-007-9183-5

Graham, M., Ates, S., Melathopoulos, A. P., Moldenke, A. R., DeBano, S. J., Best, L. R., & Higgins, C. W. (2021). Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. *Scientific Reports, 11*(1), 7452. https://doi.org/10.1038/s41598-021-86756-4

Guo, X., Li, K., Liu, Y., Zhuang, M., & Wang, C. (2022). Toward the economic-environmental sustainability of smallholder farming systems through judicious management strategies and optimized planting structures. *Renewable and Sustainable Energy Reviews, 165*, 112619. https://doi.org/10.1016/j.rser.2022.112619

Ingram, V., van Rijn, F., Waarts, Y., & Gilhuis, H. (2018). The impacts of cocoa sustainability initiatives in West Africa. *Sustainability, 10*(11), 4249. https://doi.org/10.3390/su10114249

Jezeer, R. E., Santos, M. J., Boot, R. G., Junginger, M., & Verweij, P. A. (2018). Effects of shade and input management on economic performance of small-scale Peruvian coffee systems. *Agricultural Systems, 162*, 179–190. https://doi.org/10.1016/j.agsy.2018.01.014

Kolapo, A., Tijani, A. A., Oluwatayo, I. B., Ojo, T. O., Khumalo, N. Z., Elhindi, K. M., Kassem, H. S., & Adeleye, F. A. (2025). Sustainable intensification of cocoa production under a changing climate in Southwest, Nigeria. *Frontiers in Sustainable Food Systems, 9*, 1505454. https://doi.org/10.3389/fsufs.2025.1505454

Konaté, N., Kouakou, A. K., Ouattara, Y., Jagoret, P., & Barima, Y. S. S. (2025). Evaluation of opportunity costs in cocoa production in three ecological zones in Côte d'Ivoire. *Sustainability, 17*(16), 7478. https://doi.org/10.3390/su17167478

Kongor, J. E., De Steur, H., Van de Walle, D., Gellynck, X., Afoakwa, E. O., Boeckx, P., & Dewettinck, K. (2018). Constraints for future cocoa production in Ghana. *Agroforestry Systems, 92*(6), 1767–1779. https://doi.org/10.1007/s10457-017-0082-9

Kongor, J. E., Owusu, M., & Oduro-Yeboah, C. (2024). Cocoa production in the 2020s: Challenges and solutions. *CABI Agriculture and Bioscience, 5*(1), 85. https://doi.org/10.1186/s43170-024-00310-6

Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A., & Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment International, 132*, 105078. https://doi.org/10.1016/j.envint.2019.105078

Krumbiegel, K., & Tillie, P. (2024). Sustainable practices in cocoa production: The role of certification schemes and farmer cooperatives. *Ecological Economics, 225*, 108211. https://doi.org/10.1016/j.ecolecon.2024.108211

Magarelli, A., Mazzeo, A., & Ferrara, G. (2024). Fruit crop species with agrivoltaic systems: A critical review. *Agronomy, 14*(4), 722. https://doi.org/10.3390/agronomy14040722

Mayorga, I., Mendonça, J. L. V., Hajian-Forooshani, Z., Lugo-Pérez, J., & Perfecto, I. (2022). Tradeoffs and synergies among ecosystem services, biodiversity conservation, and food production in coffee agroforestry. *Frontiers in Forests and Global Change, 5*, 690164. https://doi.org/10.3389/ffgc.2022.690164

Michel, I., Blanco, J., Manga Essouma, F., & Carrière, S. M. (2024). Complex cocoa agroforestry systems shaped within specific socioeconomic and historical contexts in Africa: Lessons from Cameroonian farmers. *Agricultural Systems, 220*, 104111. https://doi.org/10.1016/j.agsy.2024.104111

Muhammad, I. (2022). Effects of land fragmentation on agricultural production in Girei Local Government Area of Adamawa State, Nigeria. *LAUTECH Journal of Civil and Environmental Studies, 10*(2), 24–34. https://doi.org/10.36108/laujoces/2202.80.0240

Niether, W., Jacobi, J., Blaser, W. J., Andres, C., & Armengot, L. (2020). Cocoa agroforestry systems versus monocultures: A multi-dimensional meta-analysis. *Environmental Research Letters, 15*(10), 104085. https://doi.org/10.1088/1748-9326/abb053

Nordman, E. (2021). *The uncommon knowledge of Elinor Ostrom: Essential lessons for collective action*. Island Press.

Obahoundjé, S., Akpoti, K., Zwart, S., Tilahun, S. A., & Cofie, O. (2025). Implications of changes in water stress and precipitation extremes for cocoa production in Côte d'Ivoire and Ghana. *International Journal of Climatology, 45*(2), 8872. https://doi.org/10.1002/joc.8872

Odijie, M. (2018). Sustainability winners and losers in business-biased cocoa sustainability programmes in West Africa. *International Journal of Agricultural Sustainability, 16*(1), 214–227. https://doi.org/10.1080/14735903.2018.1445408

Ostrom, E. (2015). Reflections on the commons. In *The commons in history: Culture, conflict, and ecology* (pp. 1–28). MIT Press.

Pohlmann, V., Schöffel, E., Eicholz, E., Guarino, E., Scheer, G., Franz, E., & Molina, A. (2024). Corn and bean growth and production in agroforestry systems. *Agroforestry Systems, 98*(3), 943–960. https://doi.org/10.1007/s10457-024-00959-y

Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science, 362*(6417), eaav0294. https://doi.org/10.1126/science.aav0294

Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., & Rieseberg, L. (2018). Trends in global agricultural land use: Implications for environmental health and food security. *Annual Review of Plant Biology, 69*, 789–815. https://doi.org/10.1146/annurev-arplant-042817-040256

Robertson, G. P., & Swinton, S. M. (2005). Reconciling agricultural productivity and environmental integrity: A grand challenge for agriculture. *Frontiers in Ecology and the Environment, 3*(1), 38–46. https://doi.org/10.1890/1540-9295(2005)003[0038:RAPAEI]2.0.CO;2

Robertson, P., Gross, K., Hamilton, S., Landis, D., Schmidt, T., Snapp, S., & Swinton, S. (2014). Farming for ecosystem services: An ecological approach to production agriculture. *BioScience, 64*(5), 404–415. https://doi.org/10.1093/biosci/biu037

Schroth, G., Läderach, P., Martinez-Valle, A. I., & Bunn, C. (2016). From site-level to regional adaptation planning for tropical commodities: cocoa in West Africa. *Mitigation and Adaptation Strategies for Global Change, 22*(6), 903–927. https://doi.org/10.1007/s11027-016-9707-y

Schultz, T. W. (1993). *Origins of increasing returns*. John Wiley & Sons.

Shah, F., & Wu, W. (2019). Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability, 11*(5), 1485. https://doi.org/10.3390/su11051485

Song, X., Wang, X., Hu, S., Xiao, R., & Scheffran, J. (2022). Functional transition of cultivated ecosystems: Underlying mechanisms and policy implications in China. *Land Use Policy, 120*, 106195. https://doi.org/10.1016/j.landusepol.2022.106195

Sonwa, D. J., Weise, S. F., Schroth, G., Janssens, M. J. J., & Shapiro, H.-Y. (2018). Structure of cocoa farming systems in West and Central Africa: A review. *Agroforestry Systems, 93*(6), 2009–2025. https://doi.org/10.1007/s10457-018-0306-7

Touch, V., Tan, D. K. Y., Cook, B. R., Liu, D. L., Cross, R., Tran, T., Utomo, A., Yous, S., Grünbühel, C., & Cowie, A. (2024). Smallholder farmers' challenges and opportunities: Implications for agricultural production, environment and food security. *Journal of Environmental Management, 365*, 122536. https://doi.org/10.1016/j.jenvman.2024.122536

Veloso, T. C., Santana, A. C., Calvi, M. F., Azevedo Júnior, W., Gomes, S. C., Mendes, F. A., & Santana, Á. L. (2025). Sociobioeconomic effects of the transition of cocoa grown in agroforestry systems to full sun in the Amazon. *Revista de Gestão Social e Ambiental, 19*(1), e01005. https://doi.org/10.24857/rgsa.v19n1-100

Wainaina, P., Minang, P. A., Duguma, L., & Muthee, K. (2021). A review of the trade-offs across different cocoa production systems in Ghana. *Sustainability, 13*(19), 10945. https://doi.org/10.3390/su131910945

Wessel, M., & Quist-Wessel, P. M. F. (2015). Cocoa production in West Africa, a review and analysis of recent developments. *NJAS: Wageningen Journal of Life Sciences, 74-75*, 1–7. https://doi.org/10.1016/j.njas.2015.09.001

Wijerathna-Yapa, A., & Pathirana, R. (2022). Sustainable agro-food systems for addressing climate change and food security. *Agriculture, 12*(10), 1554. https://doi.org/10.3390/agriculture12101554

Wittwer, R., Bender, S., Hartman, K., Hydbom, S., Lima, R., Loaiza, V., Nemecek, T., Oehl, F., Olsson, P., Petchey, O., Prechsl, U., Schlaeppi, K., Scholten, T., Seitz, S., Six, J., & Van Der Heijden, M. (2021). Organic and conservation agriculture promote ecosystem multifunctionality. *Science Advances, 7*(42), eabg6995. https://doi.org/10.1126/sciadv.abg6995

Yang, H., Zou, R., Hu, Y., Wang, L., Xie, Y., Tan, Z., Zhu, Z., Zhu, A., Gong, J., & Mao, X. (2024). Sustainable utilization of cultivated land resources based on "element coupling-function synergy" analytical framework: A case study of Guangdong, China. *Land Use Policy, 137*, 107316. https://doi.org/10.1016/j.landusepol.2024.107316

Yu, Y., Hu, Y., Gu, B., Reis, S., Yang, L., & Zhang, F. (2021). Reforming smallholder farms to mitigate agricultural pollution. *Environmental Science and Pollution Research, 28*(34), 46072–46083. https://doi.org/10.1007/s11356-021-16610-7

Zhang, J., van der Heijden, M. G. A., Zhang, F., & Bender, S. F. (2020). Soil biodiversity and crop diversification are vital components of healthy soils and agricultural sustainability. *Frontiers of Agricultural Science and Engineering, 7*(4), 336–345. https://doi.org/10.15302/J-FASE-2020336