

Climate Shocks, Commodity Prices, and Market Connectedness: Evidence from the Ivorian Cocoa Belt

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Research Article

Keywords: Commodity market connectedness, Climate shocks, EGARCH, TVP-VAR, Cocoa markets, Financialization

Posted Date: August 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10132121/v1>

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Abstract

This paper examines how local agro-climatic conditions in Côte d'Ivoire shape global cocoa price dynamics and cross-commodity shock transmission. Using monthly satellite-derived precipitation and temperature anomalies over the period January 1980 to December 2024, we employ a two-stage framework combining an EGARCH (1,2) model with a Time-Varying Parameter VAR (TVP-VAR) to assess spillovers across cocoa, coffee, sugar, and crude oil markets. Our results show that precipitation anomalies significantly reduce cocoa returns through a supply-side channel, while conditional volatility exhibits a pronounced leverage effect and moderate persistence. TVP-VAR estimates reveal a structural break in commodity market interconnectedness around 2008, with the Total Connectedness Index nearly tripling in the post-financialization period. Prior to 2008, cocoa operated as a net transmitter of shocks within the tropical commodity complex; thereafter, it transitioned into a net receiver, primarily absorbing macro-financial shocks from oil markets. Severe climatic episodes, however, temporarily override this financial regime and restore cocoa's role as a systemic shock transmitter, a non-linear dynamic confirmed by our sub-sample robustness analysis. These findings underscore the regime-dependent interaction between agro-climatic fundamentals and commodity market financialization, with implications for climate risk management, commodity derivatives pricing, and early-warning systems for global food price instability.

Key words: Commodity market connectedness; Climate shocks; EGARCH; TVP-VAR; Cocoa markets; Financialization

JEL code: Q11, Q54, C22, C58

1. Introduction

Climate variability has emerged as one of the most important drivers of volatility in global commodity markets (Brunner 2002; Campiglio et al. 2023; Jia et al. 2023). Over the past four decades, extreme weather events have increased markedly, with the share of global cropland exposed to severe drought rising from roughly 15-16 percent in 1980 to nearly 25 percent by 2010 (OECD 2025; Eckstein et al. 2021), and climate shocks pushing tens of millions into poverty and displacing large populations across the developing world (Jafino et al. 2020; World Bank 2021). For agricultural markets, this signals a structural shift in price risk. Climate shocks increasingly function as persistent supply disruptions rather than transitory disturbances, contributing to cost-push inflation and amplified volatility through supply constraints, speculative behavior, and financial linkages (Cevik and Jalles 2023; Kotz et al. 2024; UN DESA 2024).

Among agricultural commodities, cocoa is particularly exposed. Global production is concentrated in West Africa, where Côte d'Ivoire alone accounts for roughly 45 percent of world output, and

together with Ghana for nearly 70 percent (ICCO 2024; Wessel and Quist-Wessel 2025), so that shocks in a narrow agro-climatic corridor can generate disproportionate effects on global markets. These risks are projected to intensify, with suitable cultivation areas potentially shrinking by 10-40 percent by 2050 under high-emission scenarios (Läderach et al. 2013; Schroth et al. 2016; Bunn et al. 2021). Cocoa trees are highly sensitive to rainfall and temperature extremes, and days exceeding 32°C during the main crop season have already risen markedly in Côte d'Ivoire and Ghana, reducing yields (Climate Central 2025; Akyeampong and Martin 2025); rainfall extremes alone explain nearly 68 percent of year-to-year variation in Ghanaian cocoa yields between 2000 and 2024 (Albright, Berkoh-Oforiwa, and Huybers 2025). Adverse weather across West Africa between 2022 and 2024 produced a deficit of approximately 489,000 tons in the 2023-2024 season, the largest in more than sixty years, while benchmark futures prices surpassed USD 10,000 per ton in 2024 (ICCO 2024; UNCTAD 2024).

Despite these developments, most economic models still treat climate shocks as exogenous and transitory, a framework increasingly insufficient to explain recent price dynamics. Cocoa price surges instead appear to reflect cumulative multi-year climatic stress combined with structural factors such as aging tree stocks, pest and disease pressure (cocoa swollen shoot virus alone has caused yield losses of up to 50 percent in parts of Ghana), and slow farmer adaptation, interacting with institutional structures such as administered producer prices, export policies, and political uncertainty to generate persistent volatility (Tabe-Ojong et al. 2024; Lander 2025; Karydas and Xepapadeas 2019; Caldara and Iacoviello 2022).

Financial interconnectedness further complicates this transmission. Agricultural commodities are increasingly linked through consumption and production substitution and portfolio rebalancing (Diebold and Yilmaz 2012; Ji et al. 2018; Luo et al. 2023), with tropical soft commodities such as cocoa, coffee, and sugar exhibiting strong co-movements (Ge et al. 2025). Between 2022 and 2024, drought and frost in Brazil reduced coffee and sugar output while excessive rainfall and disease in West Africa reduced cocoa supply, and prices of all three surged to multi-year highs within a similar window (World Bank 2025; UNCTAD 2024).

Despite growing research on climate impacts and commodity markets, an empirical gap remains. Indeed, most cocoa-climate studies focus on agro-ecological vulnerability rather than price dynamics (Läderach et al. 2013; Schroth et al. 2016), studies of global indices such as ENSO fail to capture country-specific conditions in the dominant producer (Brunner 2002; Ubilava 2017), and cross-commodity spillover studies typically abstract from climatic determinants altogether (Adrangi and Chatrath 2003; Ge et al. 2025).

This paper addresses this gap by asking: to what extent do local climatic conditions in Côte d'Ivoire influence the level and volatility of global cocoa prices, and how are these effects transmitted to related tropical markets such as coffee and sugar? We estimate an EGARCH model of monthly cocoa futures returns incorporating Ivorian precipitation and temperature anomalies alongside financial and commodity market variables, capturing nonlinear volatility dynamics, asymmetric shock responses, and heavy-tailed return distributions. The paper makes three contributions: new

evidence on country-level climate variability as a driver of global commodity volatility; documentation of cross-commodity spillovers between cocoa, coffee, and sugar; and evidence of asymmetric volatility dynamics in cocoa prices. Our results show that precipitation anomalies in Côte d'Ivoire significantly reduce cocoa returns, that volatility exhibits a pronounced leverage effect, that returns display significant positive spillovers from coffee and sugar, and that the heavy-tailed return distribution implies standard Gaussian models substantially underestimate extreme price risk.

The remainder of the paper proceeds as follows. Section 2 provides background on the global cocoa market, Section 3 reviews the related literature, Section 4 describes the methodological framework, Sections 5 and 6 presents the econometric results and discusses their implications respectively, Section 7 examines robustness, and Section 8 concludes.

2. Background: The Global Cocoa Market

Cocoa occupies a structurally unique position in global agricultural commodity markets. Traded on international futures exchanges, most notably the Intercontinental Exchange (ICE) in New York and the London International Financial Futures and Options Exchange (LIFFE), cocoa underpins a downstream chocolate and confectionery industry valued at approximately USD 130-140 billion globally in 2024 (Zion Market Research, 2025). Yet production is strikingly concentrated. In fact, the West African cocoa belt accounts for approximately 71 percent of world output (ICCO, 2025), and Côte d'Ivoire alone contributes over 40 percent of global supply (ICCO, 2024). This extreme spatial concentration creates a structural fragility that distinguishes cocoa from most other agricultural inputs, since a localized agroclimatic or political shock in a single country can propagate directly into global price dislocations. Production is dominated by smallholder farmers managing average plots of approximately 3 hectares (Daymond et al., 2022), constrained by limited access to inputs, credit, and agronomic extension services. Despite price stabilization mechanisms, the Conseil du Café-Cacao in Côte d'Ivoire and the Ghana Cocoa Board in Ghana, which administer floor-price and forward-sales programs, both countries remain global price-takers, with benchmark futures prices on the ICE determined by supply-demand fundamentals, speculative positioning, and macro-financial conditions beyond the control of any producing nation. The 2023/24 crisis confirmed that even well-designed domestic stabilization mechanisms cannot fully insulate producers from multi-year supply disruptions originating in climate-driven harvest failures (UNCTAD, 2024; Lander, 2025).

That season constitutes a watershed episode that starkly exposed the vulnerability of global commodity markets to localized climate shocks. The ICCO (2025) reported a final production deficit of 489,000 metric tons, the largest in over sixty years, as world gross production contracted by 12.9 percent to 4.368 million metric tons, while the global stocks-to-grindings ratio fell to approximately 26.4 percent, a 45-year low, signaling acute and sustained supply tightness. The market response was immediate and extreme, with benchmark futures prices surging above USD 10,000 per metric ton in early 2024 and peaking near USD 12,000, levels unseen since the commodity boom of the late 1970s. The proximate trigger was a confluence of adverse weather

conditions. Excessive rainfall during the main crop season triggered widespread outbreaks of swollen shoot virus and black pod disease (*Phytophthora palmivora*), degrading pod quality and accelerating crop losses (Jia et al., 2023). These shocks were compounded by structural weaknesses accumulated over decades, including ageing plantation stocks, chronic underinvestment in replanting, and the slow biological adjustment cycle of cocoa, which prevented producers from responding to strong price incentives (Lander, 2025). The episode demonstrated that the cocoa supply chain lacks the elastic response capacity of annual crop markets, rendering it disproportionately vulnerable to sustained climatic stress.

The 2023/24 crisis was not an isolated event but the most acute manifestation of a long-run structural deterioration in agro-climatic conditions across the West African cocoa belt. Albright et al. (2025) demonstrate that 68 percent of year-to-year yield variation in Ghana is explained by rainfall extremes alone, establishing precipitation variability as the single most important determinant of supply-side outcomes in the region. Climate Central (2025) reports that climate change has added at least three extra weeks per year of temperatures exceeding 32°C, a threshold associated with accelerated moisture stress and pod abortion in *Theobroma cacao*, across major growing regions over the past decade, rising to six extra weeks in 71 percent of producing areas in 2024. Long-run projections are equally sobering. Läderach et al. (2013) project that significant portions of current cocoa-growing territories in West Africa will become climatically unsuitable by the 2050s absent aggressive adaptation through altitude migration, shade management, or varietal substitution, while Schroth et al. (2016) document a progressive narrowing of the climatic envelope compatible with commercial cultivation, particularly regarding dry-season length and maximum temperature thresholds. Together, these studies establish climate change not as a future risk but as an already-active structural constraint on the world's most concentrated commodity supply chain, underscoring why understanding how these shocks transmit into global price dynamics is a prerequisite for effective risk management, early-warning systems, and climate-adaptive agricultural policy.

3. Literature Review

A substantial body of literature establishes the statistical link between climate variability and commodity market dynamics. Brunner (2002) identified the El Niño-Southern Oscillation (ENSO) as a significant determinant of global commodity price fluctuations, establishing the supply-side transmission mechanism through which atmospheric phenomena affect agricultural output and world prices. Ubilava (2017) showed that ENSO-induced price predictability is state-dependent, stronger during El Niño episodes, suggesting a non-linear relationship that standard linear models fail to capture. Letta et al. (2022) extended this to the macroeconomic level, showing that temperature shocks generate persistent output contractions in tropical economies through soil degradation, labor productivity losses, and capital depreciation. More recently, the literature has shifted toward systemic and tail risks. Campiglio et al. (2023) demonstrate correlated tail-risk spillovers across agricultural and energy futures markets, while Cevik and Jalles (2023) and Kotz et al. (2024) document that climate shocks exert upward pressure on inflation through food price transmission. A critical limitation is this literature's reliance on aggregate climate indices, which

often obscure the localized signals that determine production outcomes, a limitation this paper addresses using high-resolution, country-specific agro-climatic anomalies from Côte d'Ivoire.

A parallel literature employs the Diebold-Yilmaz (2012) connectedness framework to quantify volatility transmission across commodity and financial markets. Early contributions in the energy-agriculture nexus, notably Nazlioglu and Soytas (2011) and Zhang et al. (2010), established the channels through which oil price shocks propagate into agricultural prices via production-cost and biofuel-substitution mechanisms, with Baffes (2007) and Saghaian (2010) providing complementary evidence on input-cost transmission. Ji et al. (2018) and Luo et al. (2023) extended this framework using copula-based and frequency-domain approaches, documenting the time-varying and asymmetric nature of these channels. More recently, Ge et al. (2025) provide the most comprehensive evidence to date on volatility spillovers among cocoa, coffee, and sugar, showing that inter-market dependencies account for a substantial share of forecast error variance and that cocoa occupies a systemically important position within the tropical commodity network, while Marín-Rodríguez et al. (2025), using a TVP-VAR framework similar to the one employed here, show that climate policy uncertainty modulates the intensity of cross-commodity spillovers. Crucially, none of these studies endogenizes the climatic origins of the volatility they measure, treating connectedness as exogenous rather than as a partially climate-driven process, a gap this paper fills.

Cocoa-specific research elucidates the market's susceptibility to a complex interplay of structural and biophysical constraints. Adrangi and Chatrath (2003) provided early evidence of non-linear price dynamics in cocoa futures, while Tothmihaly (2018) documented pronounced price inelasticity of supply in West African production, amplifying the price impact of any given shock. Carr and Lockwood (2011) and Traore and Badolo (2016) examined the political economy of cocoa pricing and cross-commodity linkages, showing how governance structures and land-use competition mediate the transmission of global price signals to farm-gate outcomes. Dago and Pei (2025) provide the most direct empirical antecedent to the present study, identifying localized rainfall variability in Côte d'Ivoire as a primary driver of supply-side export shocks. Agro-ecological research provides the biophysical foundation for these findings: Läderach et al. (2013) and Schroth et al. (2016) establish that cocoa cultivation is confined to a narrow climatic envelope of 18-32°C mean annual temperature and 1,200-2,500 mm of well-distributed rainfall, with deviations generating non-linear yield losses that market-based models have historically failed to anticipate.

Despite the breadth of research surveyed above, two critical gaps persist. First, the climate-commodity literature relies on aggregate climate indices that cannot capture the localized, country-level agro-climatic anomalies that determine cocoa supply outcomes; Brunner (2002) and Ubilava (2017) identify ENSO as the key driver, but ENSO indices imperfectly reflect conditions on the ground in the southern Ivorian cocoa belt, and Dago and Pei (2025), while offering a country-level supply analysis, do not extend their findings to global price dynamics or cross-market transmission. Second, the connectedness literature treats market interdependence as a statistical property to be measured rather than a phenomenon to be explained by its climatic origins. Ge et al. (2025) and

Marín-Rodríguez et al. (2025) document the structure of volatility spillovers among soft commodities but do not identify whether these spillovers are climate-driven. This paper reconciles these two literatures by embedding high-resolution Ivorian agro-climatic anomalies into an EGARCH(1,2) framework that controls for cross-commodity spillovers from coffee, sugar, and crude oil, then feeds the purged price innovations into a TVP-VAR to estimate time-varying connectedness across the tropical commodity network, enabling a novel decomposition of cocoa price dynamics into climate-driven and systemic market-driven components.

4. Methodological Framework

This study employs a two-stage econometric framework to model the impact of local climatic shocks on global cocoa price dynamics and to quantify the subsequent shock transmission to coffee, sugar, and oil markets.

4.1. Conditional Volatility Modeling via EGARCH

We model cocoa price returns (r_t) using an EGARCH (1,2) specification (Nelson, 1991). This model is particularly suited to our analysis as it accounts for asymmetric volatility (the “leverage effect”) and incorporates exogenous climatic regressors directly into the conditional variance equation. The process is defined as:

$$r_t = \mu + \sum_{i=1}^p \phi_i r_{t-i} + \sum_{j=1}^k \theta_j X_{t,j} + \epsilon_t \quad (1)$$

where $\epsilon_t = \sigma_t z_t$ with $z_t \sim Student(v)$ $X_{t,j}$ represents the vector of exogenous variables, including climatic indicators and cross-commodity linkages. The conditional variance equation (log-variance) is given by :

$$\ln(\sigma_t^2) = \omega + \sum_{i=1}^q \alpha_i \left| \frac{\epsilon_{t-i}}{\sigma_{t-i}} \right| + \sum_{i=1}^q \gamma_i \frac{\epsilon_{t-i}}{\sigma_{t-i}} + \sum_{j=1}^m \beta_j \ln(\sigma_{t-j}^2) + \delta Z_t \quad (2)$$

where $\ln(\sigma_t^2)$ denotes the conditional log-variance. The parameter γ captures the asymmetric response to shocks, while δZ_t identifies the impact of climatic anomalies on volatility.

4.2. Shock Propagation Analysis via TVP-VAR

To assess shock transmission, we estimate a Time-Varying Parameter Vector Autoregression (TVP-VAR) model. Unlike conventional constant-parameter VAR models, the TVP-VAR framework allows for continuous parameter evolution, thereby capturing the structural shifts associated with the increasing financialization of commodity markets:

$$y_t = c_t + B_{1,t} y_{t-1} + \dots + B_{p,t} y_{t-p} + A_t^{-1} \Sigma_t \epsilon_t \quad (3)$$

$$B_t = B_{t-1} + v_t \quad (4)$$

where y_t is an $(n \times 1)$ vector of observed variables; $B_{1,t}, \dots, B_{p,t}$ are $(n \times n)$ matrices of time-varying coefficients; $\epsilon_t \sim N(0, I)$ represents structural shocks; and A_t and Σ_t capture the variance–covariance structure of the errors.

Equation (2) is the state equation describing the evolution of coefficients. The variance–covariance matrix is given by:

$$\text{Var}(\epsilon_t) = \Omega_t = A_t^{-1} \Sigma_t \Sigma_t' (A_t^{-1})' \quad (5)$$

where A_t is a lower triangular matrix capturing contemporaneous relationships between variables, with elements evolving as random walks ($a_t = a_{t-1} + \zeta_t$). The matrix Σ_t is diagonal, $\Sigma_t = \text{diag}(\sigma_{1,t}, \dots, \sigma_{n,t})$, where each standard deviation follows a stochastic process:

$$\log(\sigma_{i,t}) = \log(\sigma_{i,t-1}) + \eta_{i,t} \quad (6)$$

Following Diebold and Yilmaz (2012), we utilize the Generalized Forecast Error Variance Decomposition (GFEVD) to compute directional connectedness indices:

- Transmitted (T) : The fraction of forecast error variance in other markets explained by shocks to the cocoa price.
- Received (F) : The fraction of cocoa price forecast error variance explained by shocks to external commodity markets.
- Net (N) : The difference between transmitted and received shocks ($N = T - F$), serving as a measure of a market's role as a net shock transmitter or receiver within the system.

By applying this methodology to the standardized residuals extracted from the EGARCH model, we isolate “price innovations” from climatic fundamentals, providing a robust measurement of how local Ivorian supply-side shocks propagate through the global commodity network. This two-stage approach offers two advantages over a single-equation TVP-VAR augmented with climatic regressors. First, it allows the volatility transmission structure to be estimated on innovations that are orthogonal to the supply-side climate signal, thereby preventing the conflation of fundamentals-driven and financially-driven price co-movements. Second, the EGARCH framework explicitly models the asymmetric and non-Gaussian features of cocoa returns prior to the connectedness analysis, which improves the statistical properties of the residuals fed into the TVP-VAR. We acknowledge that the use of generated regressors introduces estimation uncertainty in the second stage that is not fully reflected in the reported standard errors; this limitation is common to two-step procedures in the commodity finance literature (e.g., Diebold and Yilmaz, 2012).

4.3.Data and source

The dataset employed in this study combines global commodity market data with high-resolution regional climatic observations, covering the period from January 1980 to December 2024, yielding 540 monthly observations for each series. The sample period is chosen to maximize coverage while remaining within the availability of consistent satellite-derived climatic data and to span multiple commodity price cycles, including the financialization episode of the early 2000s and the supply crisis of 2022–2024.

Global commodity price series – specifically cocoa, coffee, crude oil, and sugar – are sourced from the Federal Reserve Economic Data (FRED) database maintained by the Federal Reserve Bank of St. Louis (<https://fred.stlouisfed.org/>). The series used are, respectively: cocoa price, Coffee price, Sugar Price and Oil price. These four commodities are selected on the basis of well-documented substitution and co-movement relationships in the tropical soft commodity complex, as well as the central role of energy prices in agricultural production and transportation costs. All price series are expressed in US dollars and denominated at monthly frequency. They are

transformed into continuously compounded monthly log-returns, computed as $r_t = \ln(P_t/P_{t-1})$, to ensure stationarity and comparability across markets.

Climatic variables are constructed from satellite-derived monthly observations of surface temperature and precipitation obtained via the *Climate Engine* platform (<https://climateengine.org>). Unlike country-level aggregates, which would conflate agro-climatically distinct zones within Côte d'Ivoire, we restrict the spatial domain to the primary cocoa-producing regions of the country. Using the polygon selection tool available on the platform, we delineated the boundaries of the main cocoa belt, encompassing the forest and transition zones of southern and central Côte d'Ivoire where the large majority of national cocoa output is concentrated. Spatially averaged monthly values of temperature and total precipitation were then extracted for this region over the full sample period.

Raw temperature and precipitation values are converted into standardized anomalies to isolate deviations from climatological norms and to render the two climatic series dimensionally comparable. For each calendar month m and year t , the anomaly is computed as a z-score relative to the full-sample climatology: $z_{m,t} = \frac{(x_{m,t} - \mu_m)}{\sigma_m}$, where $x_{m,t}$ denotes the observed value for month m of year t , μ_m is the long-run mean of all observations for calendar month m over the baseline period 1980–2024, and σ_m is the corresponding standard deviation. This within-month standardization removes the deterministic seasonal cycle from both series and expresses each observation in units of standard deviations from the historical norm for that month, so that a value of +1 indicates conditions one standard deviation above average for that calendar month. The use of the full sample as baseline ensures internal consistency and avoids truncation of the available climatic record. The resulting series, denoted z_prec and z_temp , enter the EGARCH model as exogenous regressors in both the conditional mean and conditional variance equations.

4.4.Data analysis

Table 1 presents the descriptive statistics for all series over the full sample period. Several features of the data warrant comment. Cocoa returns exhibit the most pronounced departure from normality among the commodity series, with an excess kurtosis of 110, substantially higher than coffee (61) and sugar (41), though lower than oil (420). These extreme values indicate very heavy-tailed distributions in which large price movements occur far more frequently than a Gaussian model would predict, providing ex ante justification for the use of a Student-t distributional assumption in the EGARCH model. The negative skewness of cocoa returns (−1.0) further confirms an asymmetric distribution tilted toward large negative realizations, consistent with the leverage effect that the EGARCH framework is designed to capture. Oil returns display the highest volatility (standard deviation of 8.9%) and the most extreme kurtosis (420), reflecting the episodic nature of geopolitical and supply-side oil shocks over the sample period. The two climatic series exhibit near-zero means and unit standard deviations by construction, confirming that the z-score normalization described in Section 3 has successfully removed the deterministic seasonal cycle. The Jarque-Bera test rejects normality at the 1% level for all series except temperature anomalies, which follow a distribution closer to the normal. This result is consistent with the more gradual and mean-reverting nature of temperature variation relative to the fat-tailed dynamics of commodity prices and precipitation shocks. The Augmented Dickey-Fuller test confirms stationarity in levels for all series, so no differencing is required prior to estimation.

316

Table 1: Descriptive statistics

	Mean	SD	Skewness	Kurtosis	J-B
cocoa_ret	0.004	0.068	10.047	110.054	1760.85***
coff_ret	0.003	0.064	0.599	60.917	910.77***
oil_ret	0.005	0.089	20.498	420.400	4240.02***
sugar_ret	0.002	0.100	0.204	40.698	310.75***
z_prec	-30.21e-08	0.993	0.578	30.890	420.98***
z_temp	-30.12e-07	0.993	-0.071	20.675	50.12*

317

*** $p_value < 0.01$; ** $p_value < 0.05$; * $p_value < 0.1$

318 The presence of ARCH effects in cocoa returns is confirmed by Engle's LM test, which rejects the
 319 null of no conditional heteroskedasticity at the 1% level, validating the GARCH-family approach.
 320 For the mean equation specification, the BIC criterion selects an ARMA(1,0) process, indicating
 321 that cocoa returns exhibit first-order autoregressive dynamics but no moving-average component.
 322 The positive and significant AR(1) coefficient in the EGARCH estimates (0.141, $p < 0.05$) is
 323 consistent with mild short-run momentum in monthly cocoa futures prices, likely reflecting the
 324 gradual diffusion of supply-side information across market participants (Table 2).

325

Table 2: Determination of the ARIMA parameters

	AIC	BIC
Arma(1,0,0)	-2003.884	-1989.91*
Arma(0,0,1)	-2003.353	-1989.379
Arma(1,0,1)	-2001.9	-1983.268
Arma(2,0,1)	-2002.673	-1979.383
Arma(1,0,2)	-2004.506*	-1981.216

326

*Minimum criteria value

327 For the TVP-VAR lag order, all four information criteria (FPE, AIC, HQIC, SBIC) unanimously
 328 select a VAR(1) specification, which is retained in the estimation (Table 3).

329

330

Table 3: Determination of the VAR parameter

Lag	LL	LR	Df	P	FPE	AIC	HQIC	SBIC
0	2425.77				1.3e-09	-6.24716	-6.23561	-6.21714
1	2539.2	226.85	25	0.000	1.1e-09*	-6.47536*	-6.40606*	-6.29525*
2	2558.28	38.151*	25	0.045	1.1e-09	-6.46007	-6.33303	-6.12986
3	2567.7	18.849	25	0.804	1.1e-09	-6.41987	-6.23509	-5.93958
4	2585.38	35.363	25	0.082	1.1e-09	-6.40099	-6.15846	-5.7706

331

*Minimum criteria value

332 5. Econometric results

333 5.1. EGARCH(1,2) Estimation Results

334 *Conditional Mean Equation*

335 Table 4 reports the EGARCH(1,2) estimates for monthly cocoa futures returns over the full sample
 336 period. In the conditional mean equation, the AR(1) coefficient is positive and statistically
 337 significant ($\beta = 0.141, p < 0.05$). Returns from sugar and robusta coffee markets are positive and
 338 statistically significant, as are oil price returns ($\beta = 0.007, p < 0.01$). Precipitation anomalies in

Côte d'Ivoire carry a negative and statistically significant coefficient in the mean equation, while temperature anomalies are not significant at conventional levels.

Regarding climatic factors, rainfall anomalies in Côte d'Ivoire enter the conditional mean equation with a negative and statistically significant coefficient ($\beta = -0.0067, p < 0.05$). Temperature anomalies are not statistically significant in the conditional mean equation.

Table 4: Estimates of EGARCH(1,2) Model

<i>Mean equation</i>		<i>Variance equation</i>	
Var	Coef	Var	Coef
cons	0,0002 (0,684)	cons (ω)	-0,8861 (0,024 **)
lcocoa_ret	0,1415** (0,021)	ARCH1 (α_1)	-0,0039 (0,938)
coff_ret	0,0094*** (0,000)	GARCH1 (1) (β_1)	0,7282 (0,002 ***)
sug_ret	0,0059** (0,021)	GARCH2 (β_2)	0,1182 (0,603)
oil_ret	0,0074*** (0,002)	Asym (γ_1)	0,4670 (0,000 ***)
z_prec	-0,0067 (0,014 **)	Z_prec	0,0243 (0,664)
z_temp	-0,0007 (0,442)	Z_temp	-0,0168 (0,644)
		oil_ret	-0,0805 (0,106)
<i>Statistics</i>			
Shape (ν)	10,3317 (0,022 **)		

*** $p_value < 0.01$; ** $p_value < 0.05$; * $p_value < 0.1$

Conditional Variance Equation

Turning to the variance equation, the asymmetry parameter is positive and highly significant ($\gamma_1 = 0.467, p < 0.001$), indicating an asymmetric response of conditional variance to positive versus negative shocks.

The first GARCH coefficient is positive and statistically significant ($\beta_1 \approx 0.728, p < 0.01$), implying a volatility half-life of $h_{1/2} = \ln(0.5)/\ln(\beta_1) \approx 2.18$ months. Neither rainfall nor temperature anomalies attain statistical significance in the conditional variance equation.

The ARCH(1) coefficient is not statistically significant, while the Student-t shape parameter indicates moderately heavy tails in the return distribution. Climatic variables (rainfall and temperature anomalies) are not significant in the conditional variance equation.

The estimated Student-t shape parameter ($\nu \approx 10.33$) The ARCH(1) coefficient is not statistically significant after full estimation, indicating that short-run symmetric shock intensity does not independently drive volatility once persistence and asymmetry are accounted for.

Although the Engle test confirms the presence of ARCH effects in raw returns, the ARCH(1) coefficient (α_1) turns out to be non-significant after estimation. This result indicates that cocoa price volatility is not solely driven by immediate symmetric shocks (pure ARCH effect), but is instead dominated by strong persistence (GARCH) and, above all, by marked asymmetry (leverage effect, γ_1). Thus, the volatility structure is better explained by the differential response to price shocks (asymmetry) and by the long memory of the market (persistence), rather than by the mere occurrence of recent shocks.

5.2. TVP-VAR Connectedness Results

Time-varying transmission

Figure 1 plots the time-varying transmission coefficients from the rolling TVP-VAR model, with 95% confidence bands, for the three directional channels: *Cocoa* $\rightarrow$ *Coffee*, *Cocoa* $\rightarrow$ *Oil*, and *Cocoa* $\rightarrow$ *Sugar*. For the *Cocoa* $\rightarrow$ *Coffee* channel, the coefficient oscillates around zero over the full sample with a mild positive tendency until the early 2000s ($\beta \approx +0.2$), followed by a gradual drift toward negative values after 2010. The absence of a persistently significant non-zero coefficient suggests an unstable, regime-dependent relationship rather than a structural transmission channel, consistent with the literature on time-varying co-movements in soft commodity markets. For the *Cocoa* $\rightarrow$ *Oil* channel, the coefficients display the highest volatility of the three panels, with pronounced positive spikes around 2000 (+0.5) and 2005–2008 (+0.4), coinciding with the early phase of commodity financialization and the global energy price surge. After 2010, the coefficient stabilizes close to zero with narrower confidence bands, indicating a relative decoupling in the recent period. For the *Cocoa* $\rightarrow$ *Sugar* channel, the most distinctive profile emerges: the coefficient is clearly positive and significant between 1995 and 2010 (reaching +0.5), consistent with the substitution relationship between the two tropical crops, before reversing to negative territory after 2015. This sign reversal may reflect the progressive erosion of the historical cocoa–sugar complementarity as land-use competition and shifting demand patterns have altered relative price dynamics in the tropical soft commodity complex. Across all three panels, the 95% confidence bands are wide throughout the sample, reinforcing the interpretation of trends rather than point-in-time levels.

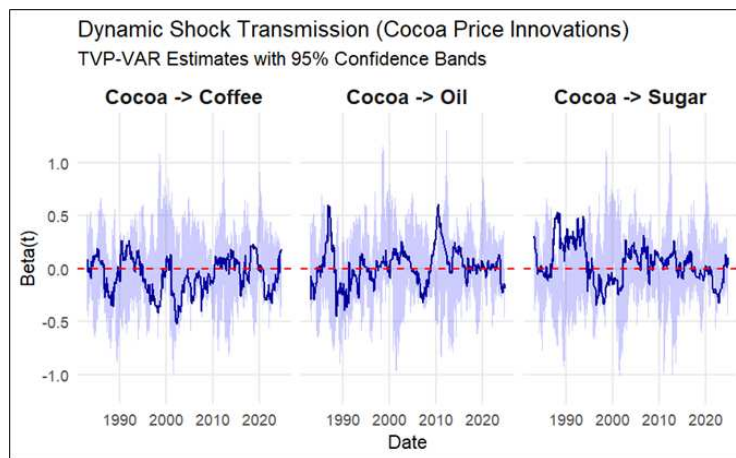


Figure 1: Dynamic shock transmission from cocoa to other markets

Figure 2 overlays the smoothed transmission coefficient trends with the precipitation anomaly series from Côte d'Ivoire, with red-shaded zones indicating dry spell episodes and blue-shaded zones indicating flood events. The figure provides direct visual evidence of the climate–transmission nexus at the heart of this paper. For the *Cocoa* → *Coffee* channel, transmission is negative and accentuated during the main dry spell episodes, particularly over 1990–1995 and 2015–2024, where the smoothed Beta descends to $-0.5/-0.6$. This pattern suggests that drought conditions affect the two crops asymmetrically, reducing rather than amplifying co-transmission.

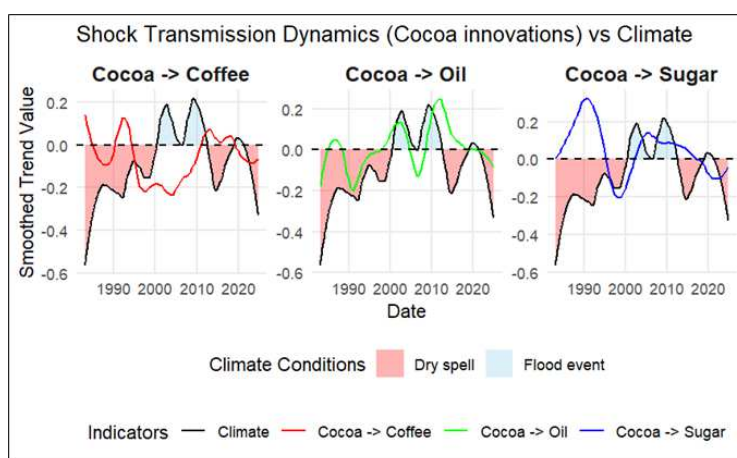


Figure 2: Shock transmission dynamics vs precipitation dynamics

This may be due to the fact that West African coffee responds differently from cocoa to hydrological deficits. For the *Cocoa* → *Oil* channel, the smoothed coefficient is positive and elevated during flood episodes (around 1995–2000 and 2005–2010, reaching $+0.2$), consistent with the interpretation that supply surpluses driven by excess precipitation amplify co-movements with energy markets via the biofuel and transport cost channels. The coefficient becomes negative from 2020 onward, coinciding with the onset of a prolonged dry spell. For the *Cocoa* → *Sugar* channel, the figure reveals the most compelling evidence of climate-driven transmission dynamics. The smoothed Beta is strongly positive during flood events ($+0.2/+0.3$) and systematically negative during dry spells ($-0.5/-0.6$), tracing an almost mirror image of the precipitation anomaly curve. This near-symmetric response is the most direct visual confirmation that climatic conditions modulate both the direction and the intensity of cocoa’s price transmission to the sugar market. The systematic temporal concordance between climatic extremes and sign reversals in the transmission coefficients, visible across all three panels, constitutes robust visual evidence that local Ivorian agro-climatic conditions are a significant determinant of global commodity market interconnectedness.

These results complement the framework of Diebold & Yilmaz (2012) regarding volatility spillovers by demonstrating that market connectedness is not an exclusively financial phenomenon, but one deeply conditioned by exogenous physical fundamentals. While studies such as Gilbert (2010) and Baffes (2007) primarily attribute agricultural price volatility to speculative behaviors and energy linkages, our findings nuance this perspective by reinstating the role of climate as a primary structural driver. We demonstrate that the Ivorian climate remains a major catalyst whose

impact is non-linear and regime-dependent. This aligns with Saghaian (2010), who emphasizes that price transmission between energy and agricultural sectors is a complex process contingent upon the prevailing economic environment. Ultimately, our study confirms that Côte d'Ivoire's climatic resilience has evolved into a key determinant of stability for the global commodity system, where local environmental shocks possess the systemic capacity to override financial drivers when supply-side fundamentals are sufficiently constrained.

Directional and Net Connectedness Indices

Figure 3 reports the time-varying Total Connectedness Index (TCI) and the directional (Received, Transmitted) and Net connectedness indices for the cocoa market over the full sample period (1980–2024). The TCI exhibits a structural upward trend over the four decades, rising from values in the range of 300–400 in the early 1980s to peaks exceeding 1,000 after 2008, before partially moderating toward the end of the sample. This near-tripling of systemic integration reflects the progressive financialization of commodity markets documented by Tang and Xiong (2012), whereby the growing presence of commodity index investors deepened co-movements across energy and agricultural assets and enlarged the fraction of price variance attributable to macro-financial shocks rather than idiosyncratic supply fundamentals. The Received index, which measures the share of cocoa price forecast error variance attributable to shocks from oil, coffee, and sugar, fluctuates between 0 and approximately 6 throughout the sample, with a pronounced peak around 2000–2005. This peak coincides with the early phase of commodity index investment and the global food price run-up, during which external macroeconomic and energy shocks began to exert increasing influence on tropical agricultural markets, consistent with the energy-agriculture transmission channel identified by Baffes (2007) and Saghaian (2010). The Transmitted index, capturing the contribution of cocoa price innovations to forecast error variance in other commodity markets, reaches its maximum of approximately 7–8 around 2005–2010, before declining progressively thereafter. This decline signals the cocoa market's gradual transition from a supply-driven price setter to a price taker within an increasingly financialized commodity network.

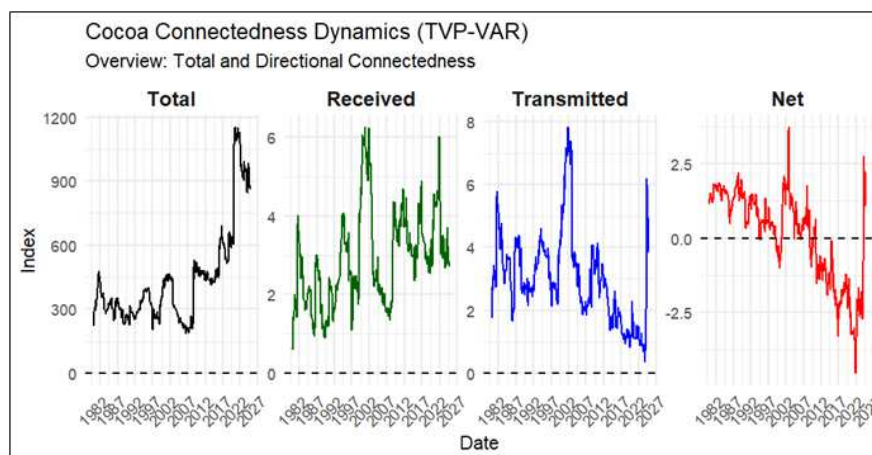


Figure 3: Market connectedness dynamics

The Net Connectedness index tells a particularly informative story about the evolving role of cocoa within the global commodity network. From 1980 through approximately 2005, the Net index is

predominantly positive, oscillating between 0 and +3, indicating that the cocoa market operated as a net transmitter of shocks. This period corresponds to a period during which Ivorian supply fundamentals were the primary driver of price co-movements across the tropical commodity complex. A notable spike to approximately +3 around 2000–2002 coincides with the politico-military crisis in Côte d'Ivoire, which generated acute uncertainty over global cocoa supply and amplified the market's outward transmission role. From around 2005 onward, the Net index progressively drifts into negative territory, reaching values between −2 and −3 for extended periods, consistent with the cocoa market's transition into a net receiver position as financialization embedded cocoa futures into broader macro-financial dynamics dominated by oil price shocks. This finding aligns with Buyuksahin and Robe (2014), who document that speculative participation in commodity futures markets deepened cross-market correlations precisely during this period. Crucially, the Net index rebounds sharply toward and briefly above zero at the very end of the sample (2022–2024), corroborating the full-sample result that severe supply-side climatic stress can temporarily override the financial integration regime and restore cocoa's role as a net transmitter of systemic shocks. The synchronized oscillations between the rolling transmission coefficients and the precipitation anomaly series, visible in Figure 2, confirm that drought episodes coincide with several of the most pronounced peaks in net transmission intensity, providing direct visual evidence of the climate–connectedness nexus that motivates the two-stage empirical framework of this paper.

6. Discussion

The negative and significant coefficient on precipitation anomalies in the conditional mean equation indicates that above-average rainfall in Côte d'Ivoire is associated with lower cocoa returns, consistent with a supply-expansion mechanism whereby favorable growing conditions raise expected output and exert downward pressure on global prices. This finding aligns with earlier agro-economic evidence on the sensitivity of cocoa yields to rainfall variability (Albright et al., 2025; Wessel & Quist-Wessel, 2015) and extends it to price formation by showing that the signal is detectable in monthly futures returns at the global level, even after controlling for cross-commodity spillovers and oil price movements, suggesting a genuine supply-side fundamental rather than a confounded financial signal. By contrast, temperature anomalies exert no statistically significant effect on either the conditional mean or variance, consistent with agronomic evidence that, at the monthly frequency, Ivorian yield variation has historically been more closely tied to water stress than thermal stress (Climate Central, 2025); as warming accelerates and days above 32°C become more frequent, the relative importance of temperature may increase, a structural change the current model does not capture.

The large and highly significant asymmetry parameter confirms that negative price shocks generate disproportionately larger increases in conditional volatility than positive shocks of equal magnitude, reflecting the leverage effect documented in equity markets and increasingly recognized in agricultural commodities (Karydas & Xepapadeas, 2022). Economically, supply disruptions create heightened uncertainty about the duration and severity of deficits, whereas positive supply surprises are more easily absorbed because inventories buffer excess supply, producing a structurally skewed risk profile in which adverse climatic shocks disproportionately

amplify volatility. The estimated volatility half-life of approximately 2.18 months indicates that shocks are absorbed relatively quickly under normal conditions, though the leverage effect implies that downside volatility episodes tend to be more persistent than this average suggests. The moderately heavy tails of the Student-t distribution ($v \approx 10.33$) confirm that extreme price events occur more frequently than a Gaussian framework would predict, with direct implications for value-at-risk measurement and derivatives pricing.

The TVP-VAR results call for interpretation on two registers, notably how financialization altered cocoa's position within the global commodity network, and the conditions under which supply-side climate fundamentals can re-assert themselves. The transition from net transmitter to net receiver around the early 2000s is consistent with the portfolio-rebalancing channel identified by Tang and Xiong (2012). As commodity index investment expanded, price innovations in oil and macro-financial assets were systematically transmitted across index constituents, including cocoa, irrespective of its idiosyncratic supply conditions, attenuating the market's response to Ivorian agro-climatic signals. This aligns with the broader evidence on financialization-driven spillovers (Diebold and Yilmaz, 2012; Marín-Rodríguez et al., 2025). Yet the reversion toward net-transmitter status at the end of the sample reveals a non-linear dynamic that purely financial models cannot capture: the 2022-2024 West African supply crisis, triggered by El Niño-induced drought, elevated temperatures, and fungal pressure on cocoa pods (UNCTAD, 2024; ICCO, 2024), generated a deficit large enough to overwhelm the financial integration regime, reverting cocoa to a price setter rather than a price taker. This threshold behavior nuances Gilbert (2010) and Baffes (2007), who attribute commodity surges primarily to speculative and energy-driven channels; our evidence instead suggests that speculation amplifies rather than initiates climate-driven price dislocations, with the agro-climatic shock as the fundamental trigger and financial integration determining the speed and breadth of its propagation. In normal times, precipitation anomalies operate as level-shifters of the conditional mean while financial integration governs how quickly these signals propagate; in periods of severe climatic stress, supply fundamentals overwhelm financial drivers, converting localized shocks into systemic dislocations. Standard linear models that ignore this threshold mechanism will systematically understate exposure during drought episodes, motivating the development of climate-indexed instruments such as weather derivatives referenced to standardized Ivorian rainfall indices.

7. Robustness Checks

To assess the stability of these findings, we re-estimate the full two-stage EGARCH-TVP-VAR framework over two sub-samples split at 2008, a well-documented structural break in the financialization of commodity markets (Tang and Xiong, 2012; Buyuksahin and Robe, 2014), to test whether the climate-price transmission mechanism predates or is an artefact of this regime.

Table 5: Sub-period EGARCH estimates

Parameters	<i>Mean Equation</i>		Parameters	<i>Variance equation</i>	
	1980-2007	2008-2024		1980-2007	2008-2024
μ	-0.00210***	0.01484***	ω	-1.10077*	-0.40165**

	(0.0000)	(0.0000)		(0.0986)	(0.0257)
lcocoa_ret	0.07606***	0.20995***	α_1	-0.06338	0.07441
	(0.0000)	(0.0000)		(0.3983)	(0.1064)
coff_ret	0.00897***	0.00534	β_1	0.51188**	1.00000
	(0.0000)	(0.2949)		(0.0261)	(0.6095)
sug_ret	0.00523***	0.00862***	β_2	0.30117	-0.06078
	(0.0000)	(0.0002)		(0.2106)	(0.9748)
oil_ret	0.00751	0.00789***	γ_1	0.48932***	0.36878***
	(0.0000)	(0.0000)		(0.0004)	(0.0006)
z_prec	-0.00633***	-0.01056***	z_prec	0.07026	0.06020
	(0.0000)	(0.0000)		(0.4063)	(0.3575)
z_temp	0.00393	-0.01334***	z_temp	-0.07008	0.07697
	(0.0016)	(0.0008)		(0.2726)	(0.6505)
			oil_ret	-0.12750	-0.06705
				(0.1138)	(0.6854)
Statistique					
ν	10.45329*	25.80409			
	(0.0770)	(0.7442)			

*** $p_value < 0.01$; ** $p_value < 0.05$; * $p_value < 0.1$

The results reported in Table 5 confirm broad parameter stability across regimes. The mean intercept reverses sign, from significantly negative pre-2008 to significantly positive thereafter, reflecting the shift from a structurally declining price environment to the sustained upward trend of the 2020s supply crisis, while AR(1) persistence rises markedly, consistent with greater momentum-driven serial dependence post-financialization. Most importantly, the precipitation coefficient remains negative and highly significant in both sub-periods and amplifies after 2008, confirming that the rainfall-return relationship is a persistent structural feature rather than a financialization artefact, consistent with greater cross-market integration magnifying the propagation of climate shocks. Temperature exhibits a sign reversal, positive pre-2008 and negative thereafter, plausibly reflecting a shift from compatible vegetative growth to thermal stress as Ivorian temperatures drifted upward (Schroth et al., 2016; Climate Central, 2025), though this should be interpreted cautiously given the shorter post-2008 sub-sample. Coffee loses significance in the mean equation after 2008 while sugar remains significant, suggesting a realignment toward a dominant cocoa-sugar nexus. In the variance equation, the leverage parameter remains positive and highly significant in both periods, confirming the robustness of asymmetric volatility, while GARCH persistence is well identified pre-2008 but becomes near-unit-root and jointly insignificant post-2008, a limitation that does not affect the mean-equation estimates central to the climate transmission analysis. Climatic regressors remain insignificant in the variance equation throughout, corroborating that climate affects price levels rather than volatility.

The TVP-VAR sub-sample results reinforce the paper's central argument. The Total Connectedness Index oscillates within a bounded 200-550 percent range before 2008 but settles on a structurally higher plateau thereafter, never falling below 800 percent and peaking above 1,400 percent around 2011-2012 and 2019-2020 (Figure 4), with the mean TCI rising from 371 to 980 percent, an

increase of 164 percent, implying that supply shocks now propagate through a far more tightly integrated network than in the pre-financialization era.

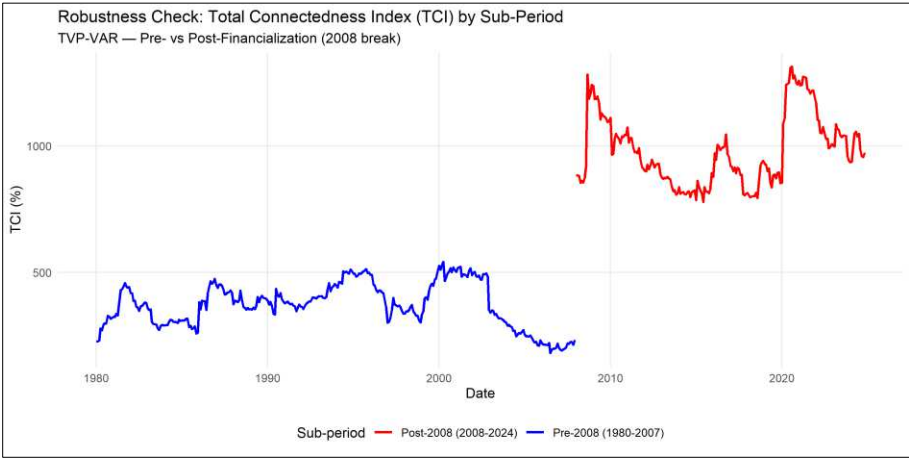


Figure 4: Two periods Total Connectedness comparison

Cocoa's directional role also reverses, with the mean Net Connectedness shifting from +1.88 (net transmitter) before 2008 to -0.74 (net receiver) after. The Net Connectedness index further confirms a clear regime shift in sign (Figure 5): structurally positive before 2008, including a spike around 2000-2002 coinciding with Côte d'Ivoire's politico-military crisis, and structurally negative thereafter as financialization embedded cocoa futures into broader macro-financial dynamics, before rebounding sharply toward and briefly above zero in 2022-2024, corroborating that severe climatic stress can temporarily override the financial integration regime. Taken together, the negative effect of precipitation on returns, the asymmetric volatility response, and the non-significance of climatic regressors in the variance equation are all preserved across regimes; the most substantive changes concern the temperature coefficient's sign reversal and the shift in cross-commodity substitution relationships.

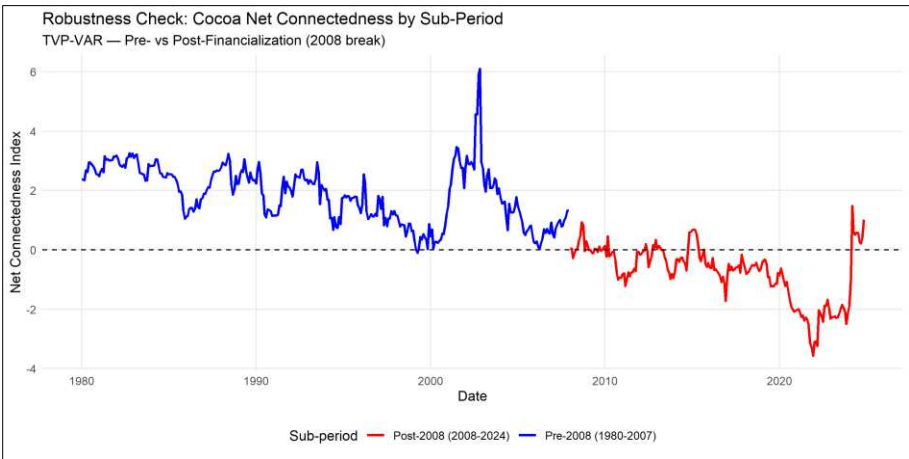


Figure 5: Two periods Net Connectedness comparison

8. Conclusion

This study examined the role of local climatic conditions in Côte d'Ivoire in shaping global cocoa price dynamics and the transmission of these shocks across interconnected tropical commodity markets. Using a two-stage framework combining an EGARCH(1,2) model with a Time-Varying Parameter VAR, we analyzed monthly data spanning January 1980 to December 2024, integrating satellite-derived precipitation and temperature anomalies from Côte d'Ivoire's primary cocoa-producing regions alongside global price series for coffee, sugar, and crude oil.

Our results yield four main findings. First, precipitation anomalies in Côte d'Ivoire exert a significant negative effect on cocoa futures returns, consistent with a supply-side mechanism whereby above-average rainfall raises expected output and suppresses global prices; this effect persists after controlling for cross-commodity spillovers and energy fluctuations, underscoring its structural character. Second, the EGARCH estimates reveal a pronounced leverage effect in cocoa volatility, whereby negative price shocks generate disproportionately larger increases in conditional variance than positive shocks of equal magnitude, and combined with the moderately heavy tails of the return distribution, this implies that standard Gaussian risk models substantially underestimate downside price risk. Third, the TVP-VAR connectedness analysis documents a structural shift around 2008, after which cocoa increasingly operated as a net receiver of shocks from oil, coffee, and sugar markets, consistent with the financialization of commodity markets. Fourth, this financial integration does not eliminate the primacy of supply-side fundamentals: during episodes of severe climatic stress, such as the 2022-2024 West African production crisis, Ivorian weather conditions reassert their role as the dominant driver of global price formation, temporarily converting cocoa back into a net transmitter of systemic shocks.

These findings contribute to three strands of the commodity finance literature. First, they extend the predominantly agro-ecological literature on cocoa vulnerability (Läderach et al., 2013; Schroth et al., 2016; Albright et al., 2025) to the domain of price dynamics, showing that country-level precipitation anomalies in Côte d'Ivoire are detectable in global monthly cocoa returns even after controlling for cross-commodity spillovers and energy prices, complementing the ENSO-based approach of Brunner (2002) and Ubilava (2017) by showing that localized, country-specific climate signals carry sufficient information to influence global price formation in the world's most concentrated commodity. Second, the findings document the regime-dependent nature of commodity market connectedness. Financialization and climatic fundamentals are not competing explanations of volatility but interact non-linearly. While Tang and Xiong (2012) and Buyuksahin and Robe (2014) document the financial integration that emerged after 2008, our results show that this integration amplifies rather than crowds out supply-side fundamentals when climatic stress is sufficiently severe, nuancing the view of Gilbert (2010) and Baffes (2007) that commodity surges are primarily speculative and energy-driven. Third, by documenting the asymmetric volatility structure of cocoa returns, the paper establishes that this market's risk profile is fundamentally non-Gaussian, extending the commodity risk literature (Karydas and Xepapadeas, 2022) to a tropical agricultural commodity with concentrated geographic supply.

These findings have important implications for policy and risk management. Monitoring precipitation anomalies in Côte d'Ivoire's southern cocoa belt offers a practical early-warning

signal for global price stress, suitable for integration into ICCO, FAO, or World Bank dashboards. For derivatives traders, the presence of heavy tails, leverage effects, and volatility persistence highlights the need for non-Gaussian, asymmetric risk models in Value-at-Risk and options pricing, since Gaussian assumptions understate drought-related downside risk. More broadly, the dependence of global cocoa supply on a narrow West African corridor underscores the urgency of diversifying production, developing climate-resilient varieties, and adopting climate-indexed instruments such as rainfall-based weather derivatives.

Several limitations should be acknowledged. These limitations include treating climatic shocks as exogenous, ignoring farmer adaptation, stabilization policies, and stock buffers, as well as data gaps and model restrictions. Future research should incorporate soil moisture and disease indicators, extend analysis to neighboring producers, and integrate IPCC scenarios for forward-looking insights.

Funding

The authors received no funding for this work.

Ethics approval and consent to participate

This study relies exclusively on publicly available macroeconomic, financial, and climatic datasets. No human participants, personal data, or experimental interventions were involved. Therefore, ethics approval and informed consent were not required. All data sources are cited appropriately, and the research complies with the ethical standards of academic publishing

Consent for publication

This manuscript does not contain any individual person's data in any form (including images, videos, or case details). Therefore, consent for publication is not applicable.

Competing Interests

The authors declare that they have no competing interests.

Author contributions

All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were carried out by Ouattara Dignakouho Pierre and Coulibaly Kigbajah

Salifou. The first draft of the manuscript was jointly written by both authors, and all authors provided critical feedback on earlier versions. All authors read and approved the final manuscript.

Availability of data and materials

The datasets generated and/or analyzed during the current study are publicly available from the Federal Reserve Economic Data (FRED) database and the Climate Engine platform, accessible at <https://fred.stlouisfed.org> and <https://climateengine.org>, respectively.

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