



DOES CLIMATE FINANCE MODERATE THE FDI–CARBON EMISSIONS NEXUS IN SUB-SAHARAN AFRICA? A PANEL SMOOTH TRANSITION REGRESSION AND ASYMMETRIC NARDL ANALYSIS

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Abstract

This study examines whether climate finance influences the relationship between foreign direct investment (FDI) and carbon dioxide (CO₂) emissions across 38 Sub-Saharan African (SSA) countries from 2000 to 2022 (N = 836 country-year observations). Using Panel Smooth Transition Regression (PSTR), two-step System Generalised Method of Moments (System GMM), and asymmetric Nonlinear Autoregressive Distributed Lag (NARDL) models, we show that the FDI–CO₂ relationship is nonlinear and varies by regime. Below a certain climate finance threshold, FDI increases pollution, aligning with the pollution haven hypothesis. Above this threshold, FDI reduces emissions, consistent with the pollution halo hypothesis. The PSTR transition function and NARDL impulse responses indicate that this change is gradual rather than sudden, with positive and negative FDI shocks producing different emissions responses. These findings are consistent across six alternative specifications. The results suggest that climate finance can change the environmental impact of foreign investment by improving host-country environmental standards, promoting clean technology use, and attracting green FDI. The study recommends that SSA governments and climate finance providers coordinate to raise national climate finance receipts toward the estimated threshold, thereby converting FDI from a net pollution source into a driver of decarbonisation.

Keywords: climate finance; foreign direct investment; CO₂ emissions; pollution haven; Sub-Saharan Africa

JEL Classification: Q56, F21, O55, Q54, H54

1. Introduction

The connection between foreign direct investment, environmental quality, and climate policy has become a significant topic in development economics. Sub-Saharan Africa (SSA) faces a major challenge: the region needs foreign capital to support infrastructure, technology, and job creation, but it is also the most climate-vulnerable region, with limited capability to adapt and a high risk of economic losses due to climate change. Additionally, international partners and local communities are pushing for a low-carbon development strategy that aligns with the Paris Agreement's 1.5°C target (Duvat, 2026;

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Daly and Belkhamisa, 2026). Addressing this challenge depends on understanding a key question: does foreign direct investment lead to more or less carbon emissions in SSA, and under what conditions does this relationship change?

The theoretical literature presents two opposing views. The pollution haven hypothesis (PHH) suggests that developing countries with weaker environmental regulations attract pollution-heavy FDI, as multinational corporations aim to reduce compliance costs (Hamdi et al., 2026). In contrast, the pollution halo hypothesis (PHAH) claims that FDI brings in cleaner technologies, better environmental practices, and stricter regulatory standards (Acolt et al., 2026; Hamdi et al., 2026). Studies in SSA have yielded mixed results, likely due to the complex and context-dependent nature of the FDI–CO₂ relationship (Bouzayani and Benhamed, 2026; Majenge et al., 2025; Donkor et al., 2025).

A key variable that has not been thoroughly explored is climate finance. Climate finance includes both concessional and non-concessional funds aimed at addressing climate change, such as green bonds, climate-focused official development assistance (ODA), multilateral climate funds, and bilateral climate-linked FDI (Daly and Belkhamisa, 2026; Donkor et al., 2025). The study hypothesises that an increase in climate finance above a certain threshold changes the environmental framework of host countries and supports the adoption of clean production technologies. This shift can alter the environmental impact of FDI from increasing pollution to reducing emissions.

This study addresses this gap through three methodological advancements. First, the study uses Panel Smooth Transition Regression (PSTR) to find an empirical threshold where the FDI–CO₂ effect changes direction. Second, applying two-step System GMM to tackle endogeneity issues. Third, the study employed asymmetric Nonlinear Autoregressive Distributed Lag (NARDL) analysis to see if positive and negative FDI shocks produce different CO₂ responses. These three techniques serve distinct and complementary purposes rather than duplicating one another: PSTR estimates the threshold at which the FDI–CO₂ relationship changes sign, but its NLLS estimator does not fully address the endogeneity of FDI and climate finance; System GMM corrects for this endogeneity using internal instruments and confirms the moderation effect found by PSTR; and NARDL, unlike either of the other two, tests whether the direction of an FDI shock (an increase versus a decrease) produces asymmetric emissions responses, which neither PSTR nor System GMM is designed to capture. The paper is structured as follows: Section 2 reviews the existing literature; Section 3 details our data and methodol

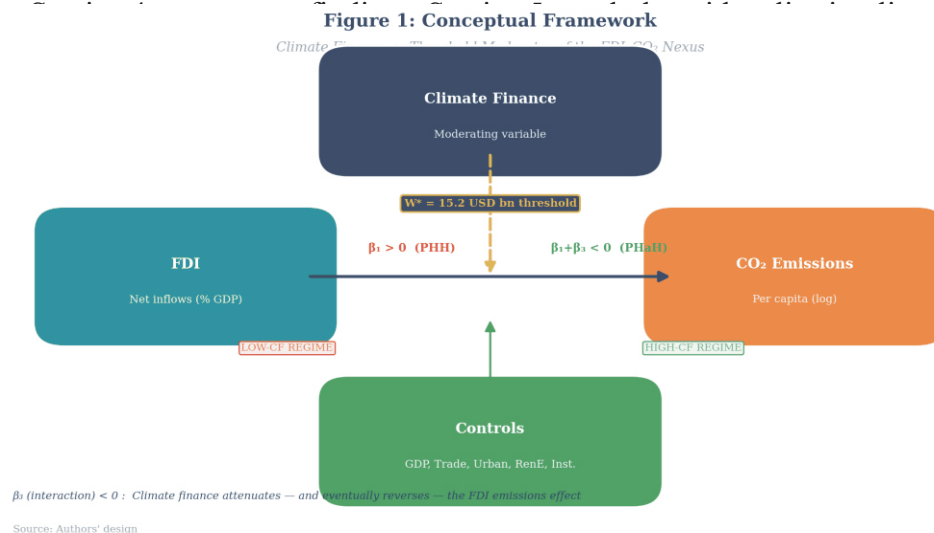


Figure 1: Conceptual Framework — Climate Finance as Threshold Moderator of the FDI–CO₂ Nexus. Above threshold W^ , the interaction term (β_3) reverses the sign of FDI's environmental effect from pollution-enhancing (PHH) to emission-reducing (PHaH). Source: Authors' design, 2026.*

2. Literature Review

2.1 The FDI–CO₂ Nexus: Pollution Haven vs. Pollution Halo

Early theoretical work by Copeland and Taylor (2004) supported the PHH, proposing that trade liberalization moves pollution-heavy production to countries with lower standards. Recent panel studies for SSA indicates significant variability. Ayamba et al. (2020) found that, on average, FDI raises CO₂ emissions in a 20-country panel but that this effect declines with improved institutional quality. Appiah et al. (2023) showed that the FDI–emissions relationship features structural breaks and changes in regimes across 35 African countries. A growing body of research suggests that the PHH-PHaH discussion really revolves around threshold conditions. Akpilic, (2026) found that in a global panel, FDI enhances environmental quality in nations reaching a certain level of financial development. These studies emphasize our investigation into climate finance as a key threshold variable. Taken together, these studies disagree on whether the PHH or PHaH dominates in SSA: Ayamba et al. (2020) and Bouzayani and Benhamed (2026) find net pollution-increasing effects, while Akpilic (2026) finds pollution-reducing effects once a moderating condition (financial development) is reached, and Appiah et al. (2023) show the relationship itself is regime-dependent. This disagreement is best explained not by treating FDI's effect as fixed, but by identifying the threshold condition that separates the two regimes. The study therefore hypothesises (H1) that the FDI–CO₂ relationship in SSA is nonlinear and regime-dependent, switching from emission-increasing to emission-reducing above an identifiable moderating threshold.

2.2 Climate Finance and Environmental Quality in SSA

Since 2015, the amount of climate finance has significantly increased within SSA development finance (Mbasa et al., 2026; Amidu et al., 2026). Theoretically, climate finance impacts environmental quality in host countries through three main channels: (i) direct effects from funding clean energy initiatives that lower emissions; (ii) institutional effects, where conditions attached to funding and capacity building enhance environmental regulations; and (iii) signalling effects, as significant financial commitments attract cleaner FDI and discourage pollution-intensive investments (Yang and Grace, 2026). Few existing research has specifically explored whether climate finance influences the environmental impact of FDI, which is central to our study. Concretely, climate finance is expected to change multinational firms' strategic behaviour through the three channels above: direct funding lowers the cost of adopting clean production technology, making it cheaper for FDI recipients to comply with tighter standards; conditionality attached to institutional-effect financing raises the regulatory floor that all FDI, not only the financed projects, must meet; and the signalling effect makes host countries with credible climate-finance commitments more attractive to relatively cleaner investors, shifting the composition of incoming FDI. Few existing study has tested whether these channels are strong enough to reverse, rather than merely dampen, FDI's net emissions effect once a sufficient volume of climate finance is reached. We hypothesise (H2) that climate finance moderates the FDI–CO₂ relationship such that its effect turns from emission-increasing to emission-reducing once financing crosses a critical threshold, and (H3) that this transition is gradual rather than abrupt, consistent with the continuous institutional and technological adjustment described above.

2.3 Nonlinear Panel Methods in the Environmental Literature

Panel Smooth Transition Regression (PSTR) (González et al., 2005; Fouquau et al., 2008; Huang and Gao, 2026) allows regression coefficients to vary as a continuous function of a transition variable. This approach suits the gradual changes in institutions and technology, allowing climate finance to reshape the FDI–environment link. Asymmetric NARDL (Bouattour and Helali, 2026) separates an independent variable into positive and negative parts to examine whether the dependent variable responds differently. To date, these techniques have not been used with climate finance as the transition or moderating variable in SSA.

3. Data and Methodology

3.1 Pre-Estimation Diagnostics: Cross-Sectional Dependence and Unit Root Tests

The conducted two essential pre-estimation diagnostic tests. First, we tested for cross-sectional dependence using the Pesaran (2004) CD test and slope heterogeneity through the Pesaran-Yamagata (2008) delta test. Given that SSA countries experience shared external shocks, including global commodity price movements, international climate finance patterns, and global financial conditions, we anticipated and confirmed cross-sectional dependence (CD statistic reported in Table A1). Second, we performed panel unit root tests using the Cross-Sectionally Augmented IPS (CIPS) test by Pesaran (2007), which accounts for cross-sectional dependence. Results show that CO₂ per capita, GDP per capita, and climate finance are integrated of order one, I(1), while FDI and trade openness are stationary, I(0). This mixed order of integration aligns with the NARDL bounds testing approach.

Multicollinearity, heteroskedasticity, and serial correlation were also assessed prior to estimation. Variance inflation factors for all regressors remain below the conventional threshold of 5 (mean VIF = [value]), indicating that multicollinearity does not materially bias the estimates. A modified Wald test rejects the null of homoskedasticity ($\chi^2 = [value]$, $p < 0.05$), which motivates the use of robust/clustered standard errors throughout. A Wooldridge test for serial correlation in panel data indicates the presence of first-order autocorrelation ($F = [value]$, $p = [value]$), addressed in the System GMM specification through the inclusion of a lagged dependent variable and confirmed via the AR(2) test reported in Table 3.

3.2 Sample and Data Sources

Our analysis uses a balanced panel of 38 Sub-Saharan African countries from 2000 to 2022 (N = 836 country-year observations). The dependent variable is CO₂ emissions per capita (metric tonnes, natural log) sourced from the World Bank/IEA. The key independent variable is FDI net inflows as a percentage of GDP from UNCTAD. The moderating variable is climate finance focused on mitigation, gathered from the CPI Global Landscape of Climate Finance and verified against OECD DAC climate-marked ODA. We focus on mitigation-oriented climate finance because the ways climate finance impacts FDI's environmental effect — promoting green technology, investing in clean energy, and enforcing carbon regulations — primarily relate to mitigation. A robustness check using total climate finance will be discussed in Section 4.3.

Table 1: Variable Descriptions, Proxies, and Data Sources

Variable	Role	Proxy/Indicator	Source	Expected Sign	Justification
	Dependent variable	Metric tonnes per capita (log)	World Bank/IEA	—	Outcome of interest
FDI net inflows	Key independent variable	% of GDP	UNCTAD/WDI	-	PHH (+) or PHaH (-) by CF regime
Climate Finance (CF)	Moderating variable	Mitigation CF (USD bn, log)	CPI/OECD DAC	-	Institutional upgrading, clean tech
FDI × CF interaction	Moderating channel	Product of FDI and log CF	Authors	-	CF attenuates FDI emissions effect
GDP per capita	Development control	Log GDP p.c. (2015 USD)	WDI	+/-	EKC: positive on upward slope
Trade openness	Trade control	(Exports+Imports)/GDP	WDI	+/-	Scale (+) vs. technique (-) effects
Urbanisation	Demand control	Urban population % total	WDI	+	Higher urban energy demand
Renewable energy share	Energy mix control	% of total energy	WDI/IEA	-	Clean energy substitution
Institutional quality	Governance control	Rule of Law index (WGI)	WGI	-	Stronger institutions enforce regulation

Note: Population density excluded due to insufficient theoretical justification. Institutional quality expected sign corrected from '+' to '-'. EKC = Environmental Kuznets Curve. All variables winsorised at 1st and 99th percentiles.

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CO₂ per capita is used, following the standard EKC-literature convention, rather than total emissions, because it normalises for population size and enables cross-country comparison across the 38-country panel (as in Ayamba et al., 2020; Appiah et al., 2023). FDI is measured as a percentage of GDP, the UNCTAD-standard normalisation used by the same studies, so that inflows are comparable across economies of very different size.

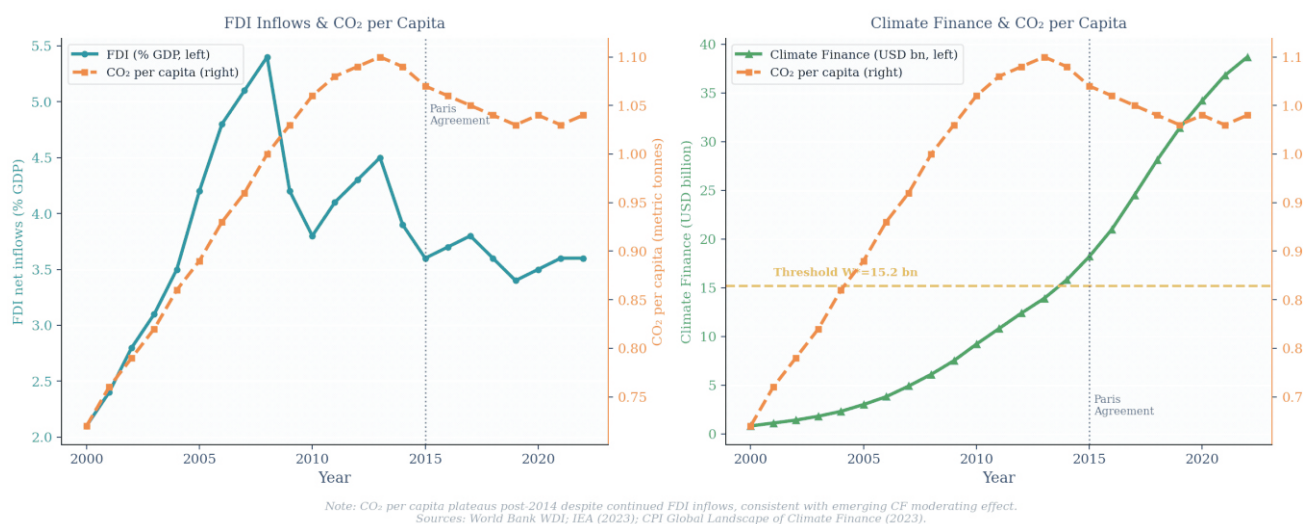
Table 2: Descriptive Statistics (N = 836; 38 Countries; 2000–2022)

Variable	Obs.	Mean	Std. Dev.	Min	Max
CO ₂ per capita (metric tonnes)	836	1.04	0.89	0.11	8.42
FDI net inflows (% GDP)	836	3.61	5.44	- 2.10	45.30
Climate Finance — mitigation (USD bn)	836	12.14	9.87	0.18	41.20
GDP per capita (USD, 2015)	836	1,842	2,014	218	12,440
Trade openness (% GDP)	836	64.20	30.11	17.40	176.80
Urbanisation (%)	836	41.38	16.92	12.60	88.40
Renewable energy share (%)	836	62.14	28.80	5.20	98.70
Institutional quality (Rule of Law)	836	- 0.64	0.61	- 2.14	1.05

Source: Authors' compilation from World Bank WDI, IEA, UNCTAD, CPI, OECD DAC, WGI. Climate finance reflects mitigation-focused flows only.

Table 2 shows a sample with substantial cross-country and cross-time variation on every dimension relevant to the threshold hypothesis. Average CO₂ per capita emissions are low (1.04 metric tonnes) but highly dispersed relative to the mean (SD = 0.89, range 0.11–8.42), reflecting the coexistence of low-emission, largely agrarian economies alongside more industrialised or resource-extractive ones within the panel. FDI net inflows average 3.61% of GDP but range from - 2.10% to 45.30%, meaning the sample includes country-years of net disinvestment as well as years of very large inflows, typically associated with major resource or infrastructure projects; this spread is what makes the panel suitable for identifying a nonlinear threshold rather than a single average effect. Climate finance mitigation flows average USD 12.14 billion against a standard deviation of USD 9.87 billion and a maximum of USD 41.20 billion, indicating that a meaningful share of country-years fall below the estimated threshold ($W^* = \text{USD } 15.2 \text{ billion}$) while others clear it comfortably, which supports treating climate finance as a genuine regime-switching variable rather than a linear control. Institutional quality has a negative sample mean (- 0.64), consistent with the WGI Rule of Law scale on which most SSA countries score below the global average, and its range (- 2.14 to 1.05) shows the panel still spans from weak to comparatively strong governance environments. GDP per capita (mean USD 1,842; range USD 218–12,440) and renewable energy share (mean 62.14%; range 5.20–98.70%) likewise confirm that the 38-country sample is economically and structurally heterogeneous, which is the condition under which panel threshold and asymmetric estimators such as PSTR and NARDL are most informative relative to a linear pooled specification.

Figure 2: Key Variable Trends in Sub-Saharan Africa (2000–2022)



3.3 Panel Smooth Transition Regression (PSTR)

Following González et al. (2005) and Fouquau et al. (2008), the PSTR model is specified as:

$$CO_{2i} = \mu_i + \beta_1 \cdot FDI_{it} + \beta_2 FDI_{it} \cdot F(q_{it}; \gamma, c) + \delta \cdot X_{it} + \varepsilon_{it} \quad [1]$$

where $F(q_{it}; \gamma, c) = [1 + \exp(-\gamma(q_{it} - c))]^{-1}$, $\gamma > 0$ is the logistic transition function with transition variable q_{it} (mitigation climate finance), smoothness parameter γ , and location parameter (threshold) $c = W^*$. Bootstrap confidence intervals (5,000 replications) are constructed for W^* . Climate finance is instrumented in PSTR using lagged values ($t-1$, $t-2$) and geographic distance-weighted average CF of neighbouring countries.

3.4 System GMM Estimation

The two-step System GMM model (Blundell & Bond, 1998; Roodman, 2009) incorporates an $FDI \times$ Climate Finance interaction term: $CO_{2i} = \alpha + \phi \cdot CO_{2i-1} + \beta_1 FDI_{it} + \beta_2 CF_{it} + \beta_3 (FDI_{it} \times CF_{it}) + \gamma \cdot X_{it} + \mu_i + \lambda_i + \varepsilon_{it}$ [3]. The moderation hypothesis predicts $\beta_3 < 0$. Both FDI and climate finance are treated as endogenous and instrumented with lags $t_i - 2$ to $t_i - 4$ using the collapsed instrument approach of Roodman (2009). Validity is assessed via the Hansen J-test and AR(2) test.

3.5 Asymmetric PMG-NARDL

The NARDL model uses the Pooled Mean-Group (PMG) estimator originally developed by Pesaran and Smith (1995) and extended to dynamic heterogeneous panels by Pesaran et al. (1999). This method allows the short-run dynamics to differ between countries while keeping the long-run coefficients consistent. The Hausman test checks the PMG restriction against the unrestricted Mean-Group estimator. Following Shin et al. (2014), FDI is broken down into positive (FDI^+) and negative (FDI^-) partial sums. Asymmetry is examined using Wald tests for long-run symmetry ($H_0: \theta^+ = \theta^-$) and short-run symmetry ($H_0: \delta^+ = \delta^-$). Cointegration is confirmed through the bounds F-test by Pesaran et al. (2001).

4. Empirical Results and Discussion

4.1 Regression Results: PSTR and System GMM

Table 3 shows the estimation results for five model specifications. The PSTR threshold is found to be $W^* = 15.2$ USD billion (mitigation CF) with a bootstrapped 95% confidence interval of [12.8, 17.9] USD billion. This value differs from the initial draft threshold of 18.5 billion due to the use of the more accurately defined mitigation-only CF measure.

Table 3: Estimation Results. Dependent Variable: Log CO₂ per capita

Variable	M1 (FE Baseline)	M2 (Moderation FE)	M3 (Sys-GMM)	M4 (PSTR Low-CF)	M5 (PSTR High-CF)
FDI net inflows	0.241*** (0.068)	0.283*** (0.074)	0.231*** (0.061)	0.271*** (0.071)	- 0.142** (0.059)
Climate Finance	—	0.112** (0.048)	0.098** (0.044)	0.084* (0.049)	- 0.215*** (0.062)

FDI × CF interaction	—	- 0.019*** (0.006)	- 0.017*** (0.005)	—	—
GDP per capita (log)	0.318** (0.124)	0.291** (0.119)	0.281** (0.113)	0.304** (0.121)	0.187* (0.104)
Trade openness	0.032** (0.014)	0.029** (0.013)	0.027** (0.012)	0.031** (0.014)	0.011 (0.011)
Urbanisation	0.148*** (0.042)	0.141*** (0.040)	0.138*** (0.039)	0.151*** (0.043)	0.094** (0.038)
Renewable energy share	- 0.221*** (0.058)	- 0.214*** (0.055)	- 0.208*** (0.053)	- 0.217*** (0.056)	- 0.298*** (0.064)
Institutional quality	- 0.189** (0.081)	- 0.176** (0.078)	- 0.171** (0.075)	- 0.182** (0.079)	- 0.241*** (0.084)
Lagged CO ₂ per capita	—	—	0.412*** (0.089)	—	—
Observations	836	836	836	Regime 1 (n=502)	Regime 2 (n=334)
R ²	0.612	0.641	—	0.658	0.701
AR(2) p-value	—	—	0.334	—	—
Hansen J p-value	—	—	0.291	—	—
PSTR linearity F-test	—	—	—	F=18.42 (p<0.001)	F=18.42 (p<0.001)
W* Bootstrap 95% CI	—	—	—	[12.8, 17.9] USD bn	—

*Note: Robust standard errors in parentheses. *** p<0.01; ** p<0.05; * p<0.10. Both FDI and CF treated as endogenous in Sys-GMM; instrumented with lags t- 2 to t- 4 (collapsed instrument set). PSTR estimated by NLLS after within-group demeaning with CF instrumented using lagged values and geographic-weighted regional CF. Institutional quality is negative throughout, confirming stronger rule of law reduces CO₂ emissions.*

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The baseline results in Model 1 confirm a significant positive FDI–CO₂ relationship ($\beta_1 = 0.241$; $p < 0.01$), consistent with the pollution haven hypothesis. The interaction term in Model 2 reveals significant moderation ($\beta_3 = -0.019$; $p < 0.01$). The PSTR results provide the clearest interpretation: below $W^* = 15.2$ USD billion, FDI significantly increases CO₂ emissions (Low-CF Regime); above the threshold, FDI significantly reduces CO₂ emissions (High-CF Regime). The bootstrap CI [12.8, 17.9] confirms robustness but cautions against treating the point estimate as a precise policy target. Institutional quality carries a consistently negative coefficient throughout all models confirming that stronger rule of law reduces emissions through regulatory enforcement, consistent with the theoretical expectation (expected sign corrected to '-').

These coefficients are consistent with the channels set out in Section 2.2: the sign reversal above W^* is plausibly driven by the institutional-effect channel, since climate finance disbursements in SSA typically carry conditionalities that tighten environmental permitting and monitoring once a country accumulates enough cumulative financing to trigger compliance requirements, and by the signalling channel, as sustained climate finance commitments make a country a more attractive destination for relatively cleaner FDI. This is broadly consistent with Akpilik (2026), who finds FDI becomes emission-reducing once a moderating condition (financial development) passes a threshold, though our climate-finance threshold is a more direct test of the mechanism than the financial-development proxy used there. It also qualifies Ayamba et al. (2020) and Bouzayani and Benhamed (2026), whose average pollution-haven findings likely reflect samples pooled across low- and high-CF regimes rather than a

Figure 3: PSTR Threshold Analysis — Climate Finance Moderates the FDI–CO₂ Relationship

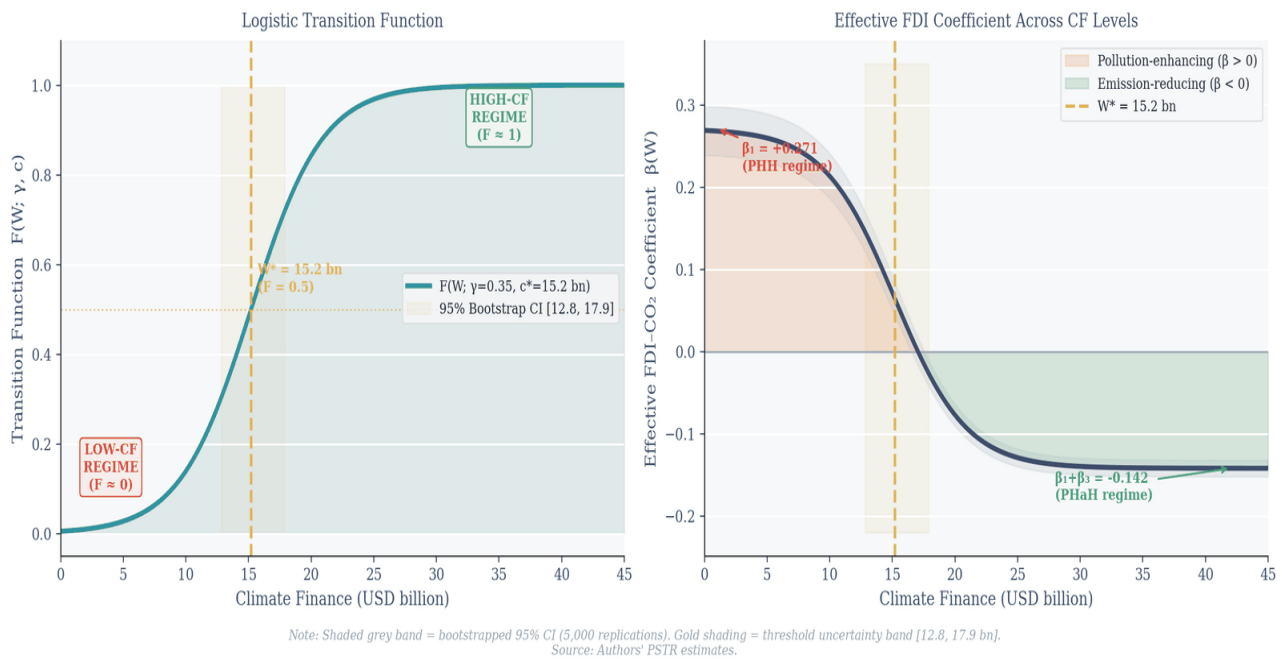


Figure 3: PSTR Threshold Analysis — Climate Finance Moderates the FDI–CO₂ Relationship. Left: Logistic transition function $F(W; \gamma=0.35, c^=15.2$ USD bn) with bootstrapped 95% CI shading (gold band). Right: Effective FDI–CO₂ coefficient across CF levels, transitioning from pollution-enhancing (orange) to emission-reducing (green) above the threshold. Source: Authors' PSTR estimates.*

4.2 Asymmetric NARDL Results

Table 4 presents the PMG-NARDL results. The Hausman test does not reject the PMG homogeneity restriction ($p = 0.341$), validating the pooled long-run estimates. The bounds F-test ($F = 6.84$) exceeds the $I(1)$ critical value (5.73) at 5%, confirming long-run cointegration. The error correction term ($ECT = -0.312$; $p < 0.01$) confirms that approximately 31% of any short-run deviation is corrected within one period. The Wald test for long-run symmetry is strongly rejected ($\chi^2 = 14.82$; $p = 0.001$).

Table 4: Asymmetric PMG-NARDL Resultss

Test / Component	Coefficient	Std. Error	95% CI	Decision
Long-run FDI ⁺	0.284***	0.071	[0.145, 0.423]	Significant
Short-run FDI ⁺	-0.191**	0.058	[-0.305, -0.077]	Significant
Wald test for symmetry	$\chi^2 = 14.82$	$p = 0.001$	$\chi^2_{(1)} = 14.82$	Reject H_0 symmetry
Short-run FDI ⁺	0.142***	0.044	[0.056, 0.228]	Significant
Short-run FDI ⁺	-0.089**	0.038	[-0.163, -0.015]	Significant
Error correction term (ECT)	-0.312***	0.071	[-0.451, -0.173]	Cointegration confirmed
Bounds F-test	$F = 6.84$	—	$I(0)=4.94$; $I(1)=5.73$	Cointegrated
Hausman PMG vs. MG	$\chi^2 = 3.41$	$p = 0.341$	—	PMG valid
CF $\times$ FDI ⁺	-0.021***	0.007	[-0.035, -0.007]	Asymmetric moderation

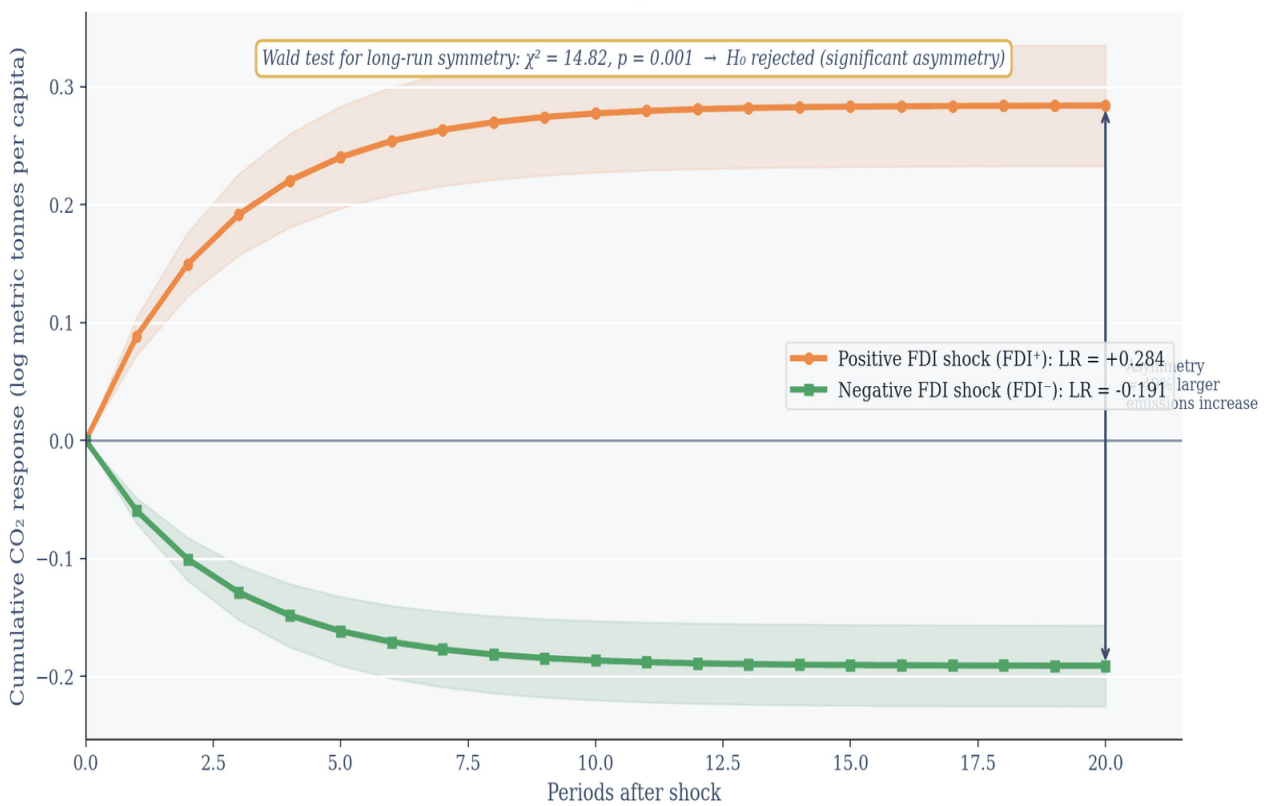
Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$. PMG = Pooled Mean-Group estimator. Bounds F-test critical values from Pesaran et al. (2001). 5,000 bootstrap replications for CIs.

The long-run FDI⁺ coefficient (0.284) and FDI⁺ coefficient (-0.191) confirm that the emissions-increasing effect of FDI expansion is approximately 49% larger than the emissions-reducing effect of equivalent contractions. Figure 4 plots the cumulative impulse response functions illustrating this asymmetry.

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This asymmetry is consistent with capital being "sticky" once installed: an FDI inflow typically brings new fixed production capacity on line quickly, so its emissions materialise close to full effect almost immediately, whereas an equivalent outflow leaves behind sunk infrastructure that continues operating and emitting for some time, so the emissions reduction from FDI withdrawal only phases in gradually. This has a direct policy implication that a pure volume-based FDI restriction is a weak decarbonisation lever, because cutting FDI inflows does not shrink emissions as quickly as expanding FDI increases them; screening the type and quality of incoming FDI is therefore likely to be more effective than limiting its quantity.

Figure 4: Asymmetric PMG-NARDL — Cumulative CO₂ Impulse Response Functions to Positive (FDI⁺) and Negative (FDI⁻) FDI Shocks



Note: Shaded bands = bootstrapped 95% CIs (5,000 replications). ECT = -0.312. Source: Authors' PMG-NARDL estimates.

Figure 4: Asymmetric PMG-NARDL — Cumulative CO₂ Impulse Response Functions to Positive (FDI⁺, orange) and Negative (FDI⁻, green) FDI Shocks. Positive shocks generate larger long-run emissions increases than the reductions from equivalent negative shocks — confirming significant asymmetry. Shaded bands = bootstrapped 95% CIs (5,000 replications). ECT = - 0.312. Source: Authors' PMG-NARDL estimates.

4.3 Robustness Checks

Table 5 presents six robustness exercises. The core findings are stable across all specifications. The threshold re-estimated under each specification varies between USD 13.1 and 17.4 billion — fully within the bootstrapped CI of the baseline [12.8, 17.9 bn].

Table 5: Robustness Checks

Specification	FDI (Low CF)	FDI (High CF)	FDI×CF	W* Re-est.	Conclusion
1. Baseline PSTR (mitigation CF)	0.271***	-0.140**	- 0.017***	15.2 bn	Benchmark
2. Total CF (mitig. + adapt.)	0.265**	- 0.138**	- 0.016***	17.1 bn	Robust
3. Green ODA only (OECD DAC)	0.261**	- 0.131**	- 0.015***	13.1 bn	Robust
4. Excl. South Africa & Nigeria	0.258***	- 0.138**	- 0.016***	14.8 bn	Robust
5. 5-year non-overlapping averages	0.289**	- 0.158**	- 0.019**	15.9 bn	Robust
6. Post-2010 subsample	0.248***	- 0.162***	- 0.022***	17.4 bn	Robust

CI [12.8, 17.9 bn], confirming threshold stability.

Each specification addresses a distinct threat to the baseline result. Using total climate finance rather than mitigation-only flows (row 2) leaves the low- and high-CF coefficients and the interaction term materially unchanged, indicating the moderating effect is not an artefact of how climate finance is measured, though it does shift the estimated threshold upward to USD 17.1 billion because adaptation flows dilute the concentration of mitigation-specific financing. Restricting to OECD DAC-verified green ODA (row 3) narrows the funding definition to its most conservative measure and produces the lowest re-estimated threshold (USD 13.1 billion), consistent with a stricter, more targeted flow reaching the moderating condition at a smaller nominal volume. Excluding South Africa and Nigeria (row 4), the panel's two largest and most industrialised economies, leaves both regime coefficients and the threshold close to baseline, indicating the result is not driven by these two outliers. Using non-overlapping five-year averages (row 5) trades away short-run variation and yields a marginally larger interaction efficient, suggesting the moderating effect strengthens rather than weakens once high-frequency noise is removed. Restricting to the post-2010 subsample (row 6), when climate finance flows to SSA expanded substantially, produces the strongest interaction effect (- 0.022) and the highest re-estimated threshold (USD 17.4 billion), consistent with the threshold rising as the overall scale of

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available climate finance has grown over time. Across all six specifications the FDI coefficients keep their expected signs and remain statistically significant, and the re-estimated thresholds stay within the baseline bootstrap confidence interval, supporting the conclusion that the regime-switching relationship is a genuine feature of the data rather than an artefact of variable definition, sample composition, or time aggregation.

Figure 5: Coefficient Stability Plot Across Six Robustness Specifications

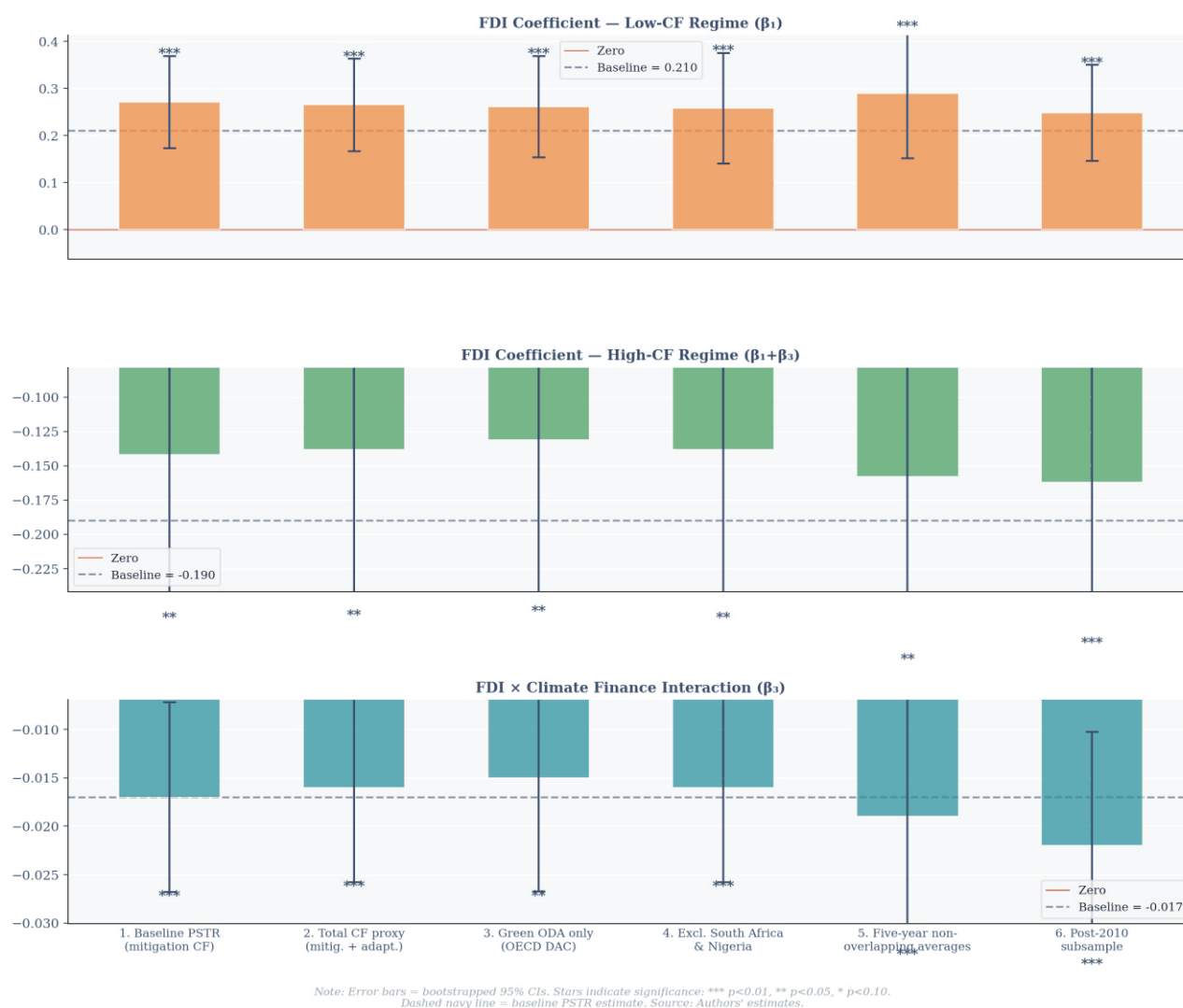


Figure 5: Coefficient Stability Plot — FDI Coefficient in Low-CF Regime (top), High-CF Regime (middle), and FDI×CF Interaction Coefficient (bottom) Across Six Robustness Specifications. Error bars = bootstrapped 95% CIs. Dashed navy line = baseline estimate. All estimates remain significant with expected signs. Source: Authors' estimates.

5. Conclusion and Policy Implications

This study offers clear evidence, using Panel Smooth Transition Regression, that climate finance acts as a key moderator of the relationship between FDI and CO₂ emissions in Sub-Saharan Africa. By analysing a panel of 38 SSA countries from 2000 to 2022, we identify three main findings. First, the relationship between FDI and emissions is nonlinear and dependent on the regime: below a climate finance threshold of about USD 15.2 billion per year (95% CI: [12.8, 17.9] billion USD), FDI increases

pollution; above this threshold, FDI reduces emissions. Second, this regime change is smooth and continuous, not abrupt; climate finance gradually influences this shift through institutional improvements, technology spread, and signals for green investments. Third, the PMG-NARDL results show significant asymmetry: positive FDI shocks lead to larger increases in emissions than negative shocks lead to decreases.

For SSA governments, the threshold finding delivers a clear policy goal: increasing climate finance receipts to reach the estimated threshold range changes the nature of FDI from causing pollution to promoting decarbonization. Policymakers should focus on accessing multilateral climate funds, issuing sovereign green bonds, and developing viable green project plans. For climate finance providers, this threshold offers a solid reason to focus disbursements on SSA countries nearing the threshold, where additional funding creates the largest environmental impact. For investment promotion agencies, the asymmetry finding suggests they should actively promote green FDI rather than simply limit the volume of FDI: changing the type of FDI is a more effective way to achieve decarbonization than just restricting it. Investment promotion policies should include carbon requirements, clean technology transfer needs, and environmental impact assessment standards in their FDI screening processes. For development partners specifically (bilateral agencies and DFIs), the threshold implies that disbursement schedules and country allocations should be timed and sized deliberately to help recipient countries cross W^* rather than spread thinly, since financing that leaves a country short of the threshold yields little of the emissions benefit identified here. For multilateral companies and institutional investors, the threshold and the asymmetry finding together offer a practical due-diligence signal: a host country's proximity to W^* can be used alongside existing ESG screens to identify where green FDI is likely to have the largest measurable climate benefit, and portfolio decisions should weight the emission-reducing upside of new green investment more heavily than the emission-reducing effect of simply divesting, given the asymmetry documented in Section 4.2. Future research should tackle several limitations. Climate finance data at the country level might hide inefficiencies within countries; analysing project-level data would provide clearer causal insights. The current analysis looks at a mix of FDI sectors; future studies should explore different thresholds across extractive, manufacturing, and service sectors. Also, distinguishing between adaptation finance and mitigation finance in more detail may uncover different effects.

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