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Nonlinear Impact Of Foreign Direct Investment And International Trade On Environmental Sustainability In Sub-Saharan Africa

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Abstract

This research analyzes the nonlinear influences of foreign direct investment (FDI) and international trade (ITR) on environmental sustainability (ES) in Sub-Saharan Africa (SSA). The ecological footprint (EFP) as well as the log of biocapacity (lBCP) in global hectares per capita serve as integrated proxies for environmental sustainability. The Method of Moments Panel Quantile Regression (MM-PQR) is employed to verify the non-linear relationships between economic variables (FDI and ITR) and environmental outcomes across the distribution of sustainability (low, medium and high) based on the annual panel data from 34 SSA economies from 1990 to 2024 (1,190 observations). The results show that FDI and ecological footprint display statistically significant curvature only among high-ES economies (Q0.75), where the positive squared term suggests that the environmental cost of FDI accumulation intensifies once a country has already attained a relatively favourable sustainability position, whereas the low- and moderate-ES quantiles show no significant curvature. For biocapacity, in contrast, the squared FDI and squared trade terms are statistically significant across nearly all quantiles, indicating that the regenerative side of environmental sustainability responds to both FDI and trade in a distinctly nonlinear way, a pattern that had not been previously confirmed in the SSA literature. International trade retains a consistently negative linear relationship with ecological footprint and a consistently positive linear relationship with biocapacity across all quantiles, with only mild curvature that reinforces rather than reverses these linear patterns. A sensitivity check comparing the full sample (1990–2024) with the observed-data sample (1990–2023) confirms that these relationships are not driven by the extrapolated final year of data. The findings imply that FDI-related environmental policy in SSA cannot rely on a single, economy-wide threshold; instead, phased environmental audits for FDI-intensive sectors, green investment incentives, and environmental clauses in trade agreements should be calibrated to a country's position on the sustainability distribution, with particular attention to the biocapacity risks that emerge once FDI accumulation surpasses moderate levels.

Keywords: FDI, international trade, nonlinear relationship, environmental sustainability, ecological footprint, biocapacity, panel quantile regression, Sub-Saharan Africa

JEL Classification: F21, F18, Q56, Q53, C23

1. Introduction

Global warming and climate change are now the most pressing problems facing the twenty first century, with industrial and anthropogenic activities as the main contributors to the emissions of GHGs and environmental degradation (World Meteorological Organisation [WMO], 2024; International Energy Agency [IEA], 2025). Pollutants such as carbon dioxide (CO_2), which result from the combustion of fossil fuels by manufacturing companies, result in environmental conditions that are not sustainable (United Nations Environment Programme [UNEP, 2023]). Land degradation and biodiversity loss are problems that have worsened in Sub-Saharan Africa (SSA) due to rapid urbanisation, deforestation, mining, agricultural expansion and infrastructure development (Li, Ren, & Zeng, 2024). Between 2001 and 2022, countries like Nigeria and the Democratic Republic of the Congo saw a decline in their forest areas by about 13% (Global Forest Watch, 2023) and in some areas like the Niger Delta and the Sahel, climate variability has increased droughts, floods and displacement (Dimuna, Ekhaese, & Ndimako, 2024).

Environmental sustainability means using natural resources wisely in order to satisfy current needs without compromising the ability of future generations to meet their needs. It includes the elements of air and water quality, pollution, noise, access to open space, health impacts of environmental conditions, physical, and mental (European Environmental Agency [EEA] 2023, 2024). In 2022, CO_2 accounted for 71.6% of global GHGs, with methane following at 21.0% (Joint Research Centre [JRC] 2023). Inventories of greenhouse gas emissions show that South Africa is the only SSA economy in the top 15 global emitters, with a 0.99% contribution (JRC, 2023).

Ecological footprint (EFP) and biocapacity (BCP) per person are complete indicators of sustainability. Ecological footprint is a measure of human demand on nature for the biologically productive land and water area needed to produce the resources used and to absorb the wastage produced. The biocapacity is the ability of ecosystems to regenerate resources and absorb wastes. Southern Africa has the highest ecological footprint (EF) in SSA with an average of more than 1.5 global hectares per person, related to industrialised economies including South Africa. The ecological footprints of the West, Middle and East African regions are just over 0.5 gha per person (Global Footprint Network, 2023). Since 1961, biocapacity per person has been decreasing steadily over SSA, meaning that consumption is becoming greater than the Earth's regenerative capacity (Global Footprint Network, 2023).

Foreign direct investment (FDI) and international trade (ITR) are important pathways of economic development and at the same time are important avenues for the spread of environmental pressures. FDI is the cross border movement of financial, technological and knowledge assets that allows investors to invest in and run business in another country. FDI can have an impact on promoting economic growth and technological innovation, but its environmental impact is a matter of debate. The term "pollution haven" hypothesis refers to the transfer of pollution-prone industries to developing countries that have weak environmental laws, resulting in higher carbon emissions and environmental degradation in importing countries (Gök, Ashraf, & Jasinska, 2024; Kayani, Nasim, Aysan, Bashir, & Iqbal, 2024). On the other hand, the "pollution halo" hypothesis states that FDI brings in cleaner technologies and management practices that could help to mitigate environmental impacts (Yi, Hou, & Zhang, 2023).

The relationship between trade openness and environmental quality is equally difficult to understand. Trade can help bring cleaner technologies and better resource use to the market, leading to lower emissions in the long run (Wang et al., 2025). However, complementary environmental regulations are needed if the expansion of trade does not lead to environmental degradation, which is often the case in resource-dependent economies (Oumarou & Nourou, 2024; Ifere et al., 2025).

Most importantly, the current literature has a strong focus on a linear relationship between FDI, trade, and environmental variables. An objective of this study is to test the assumption with the aim of exploring if any U-shaped or inverted U-shaped relationships exist between these economic variables and environmental sustainability in SSA. The potential for negative impacts of FDI and trade to emerge as these activities grow as they are added to the environment (and vice versa) has significant policy implications. If there are such non-linearities, the policy maker needs threshold-based interventions instead of a one-size-fits-all approach.

This study primarily aims to estimate the non-linear effect of FDI and international trade on environmental sustainability in SSA. The specific objectives include: (1) to explore the linear and nonlinear impacts of FDI on environmental sustainability; (2) to explore the linear and nonlinear impacts of international trade on environmental sustainability; (3) to examine if such nonlinear relationships differ at various levels of sustainability of the environment (low, medium and high); and (4) to draw policy implications from the identified nonlinear dynamics.

The following hypotheses are tested:

- **H_{01}:** The effect of FDI on environmental sustainability in SSA is not statistically significant.
- **H_{02}:** The effect of international trade on environmental sustainability in SSA is not statistically significant.
- **H_{03}:** There is no significant nonlinear (U-shaped or inverted U-shaped) relationship between FDI and environmental sustainability in SSA.
- **H_{04}:** There is no significant nonlinear (U-shaped or inverted U-shaped) relationship between international trade and environmental sustainability in SSA.

The importance of this study is that it can inform on the design of threshold sensitive policies. However, if the relationship between FDI and ecological footprint is U-shaped, it can be said that the first phase of FDI increases can have positive impacts on sustainability due to the technology transfer, but after a certain level scale effects can take precedence and worsen the ecological footprint. Analyzing these dynamics allows to establish regulatory frameworks that can be implemented in stages while recognizing the importance of green investments and including environmental factors in trade agreements.

The geographical scope of the study focuses on Sub-Saharan Africa (SSA), with data on 34 economies available: Benin, Botswana, Burkina Faso, Burundi, Cape Verde, Cameroon, Central African Republic, Chad, Democratic Republic of Congo, Republic of Congo, Ivory Coast, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Madagascar, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, South Africa, United Republic of Tanzania, Togo, Uganda, Zambia, Zimbabwe. Therefore, the dataset covers a period of 35 years from 1990 to 2024.

2. Literature Review

2.1 Conceptual Framework

Foreign direct investment (FDI) is an investment made by an entity that has a long-term relationship with an enterprise and a lasting interest and control in the enterprise residing in another economy (International Monetary Fund [IMF], 1993, 2001). FDI includes equity capital, profits remitted, and loans from the investing firm to the firm that receives the investment, as the investor has a strong influence on the management of the recipient firm. In this study, FDI is reported in terms of net inflow in percentage of GDP. International trade (ITR) is the trade of goods, services and capital between countries. It increases market opportunity, helps in technology transfer and optimizes resource use. Trade is the total value of exports plus imports of goods and services as a percentage of GDP.

The concept of environmental sustainability is presented by two complementary indicators: EFPs and BCPs. Ecological footprint indicates how much ecosystem is being demanded by humans, measured in gha/capita, and biocapacity indicates how much ecosystem is available to regenerate, measured in gha/capita. If ecological footprint is greater than biocapacity, then it creates an ecological deficit, which means that the consumption of resources is unsustainable. These indicators capture the consumption dimension of environmental sustainability which is broader than just a specific pollutant indicator such as CO_2 emissions.

2.2 Theoretical Framework

This study's theoretical foundations are based on the Pollution Haven Hypothesis (PHH). This hypothesis was theorized by Copeland and Taylor (1994) who argued that business firms create unrest and move from developed to developing countries due to free trade policies of the latter. From the affirmation of the previous theory, it can be concluded that FDI and trade are believed to be of greater risk in countries with poorly enforced regulations. According to the PHH, stricter regulations mean that there will be less pollution. Environment Kuznets Curve (EKC) is a hypothesis that states that environmental pollution follows an inverted U curve that is determined by the level of income. Initially, environmental pollution is believed to rise and reach its maximum point at a certain level of income, after which it starts declining (Grossman and Krueger, 1991, 1995). Although EKC refers to income, its principles can also be applied to other economic phenomena such as FDI and international trade as during an early stage of development some countries experience pollution due to the increase of fast growth, but as development advances the economy will take another approach and use cleaner production methods. The Pollution Halo Hypothesis (PHH) is countered by the Pollution Halo Hypothesis itself. The PHH hypothesis suggests that environmental regulations are stricter in the origin country for multinational companies compared to the foreign country and that the country of origin transmits cleaner technologies as well as environmental management systems to the host country, which results in improved environmental quality (Zarsky, 1999). With regard to this hypothesis, it is assumed that Foreign Direct Investments (FDI) can also play a role in reducing ecological degradation through technological spillovers and improvements in efficiency. In addition, this paper adapts these theories to a test for nonlinearity. In line with this idea, it may be said that the dependency between FDI and ecological footprint is expected to be U-shaped. If there were an inverted U-shaped relationship, it would mean the opposite of the above: degradation at first, followed by an improvement. These nonlinear patterns correspond with the theoretical conflict between the PHH and the pollution halo hypothesis, with the predominant effect changing with increasing levels of FDI or trade.

2.3 Empirical Literature on Nonlinear Relationships

Empirical evidence of the relationship between FDI and environment is found to be fairly heterogeneous, indicating that the linear specification might mask important nonlinear dynamics. Jinapor, Abor and Graham (2025) uncovered nonlinearity between FDI and inclusive growth in 32 SSA economies, suggesting that the impact of FDI differs across different accumulation levels. Ganda and Panicker (2025) applied double threshold regression model in 45 SSA countries and concluded that carbon emission decreased in the initial phase of FDI, but increased or decreased in the subsequent phase.

Piabuo et al. (2024) analyzed the land-use change emissions due to FDI in 30 tropical forest countries, and identified U-shaped and inverted U-shaped relationships in the Congo basin and Amazon countries, respectively, and in the Southeast Asian countries. The findings of this cross-regional variation highlight the context-dependency of nonlinear relationships. Gök et al. (2024) explored the nonlinear association between CO_2 emissions and inflows of FDI into 124 countries and revealed an inverted U-shaped relationship: pollution haven and green haven hypotheses in different emission ranges. Siripi et al., (2024) analyzed the determinants of FDI, technological innovation and carbon emissions in Ghana, and observed that FDI has a negative effect on emissions in the short run, and a positive effect in the long run, a finding that is consistent with both PHH and EKC hypotheses and implies that there are time-invariant non-linearities. Mustafa, Mordi, and Elamer (2025) showed that FDI has negative effects on renewable energy sustainability in 81 countries with a threshold effect in the presence of weak institutional standards. In the case of trade, Edoja, Aye, and Gupta (2024) applied quantile regression to Nigeria and identified significant differences in the percentile values, implying that the impacts of agricultural trade on carbon footprints are nonlinear. In emerging Asia, an analysis by Taghizadeh-Hesary et al. (2022) shows that the relationship with environmental indicators is concave, but this remains to be validated for SSA.

The literature gap is then apparent as the literature has identified U-shaped and inverted U-shaped relationships between FDI, trade and ecological footprint/biocapacity in individual studies across country/regional levels but few studies have conducted comprehensive panel quantile analyses across the full distribution of ecological footprint/biocapacity in SSA. This study is filling this gap by using MM-PQR to investigate if these nonlinear relationships differ between low, moderate and high environmental sustainability economies.

3. Methodology

3.1 Research Design

This study adopts an ex-post facto research design using secondary panel data. This design is appropriate for examining historical relationships and deriving predictive inferences about nonlinear dynamics.

3.2 Model Specifications

The analysis proceeds through two complementary model specifications for each environmental sustainability indicator:

Model 1: Linear Effects

$$lnESit=\alpha0+\alpha1FDIit+\alpha2ITRit+\alpha3lRENit+\alpha4lECAit+\alpha5lURBit+\vartheta it$$

Model 2: Nonlinear Effects (Quadratic Specification)

$$lnESit=\alpha0+\alpha1FDIit+\alpha2FDIit2+\alpha3ITRit+\alpha4ITRit2+\alpha5lRENit+\alpha6lECAit+\alpha7lURBit+\vartheta it$$

Where:

- *ESit* = Environmental sustainability for country *i* at time *t* , proxied by ecological footprint (EFP) and log of biocapacity (lBCP)
- *FDIit* = Foreign direct investment, net inflows (% of GDP)
- *FDIit2* = Square of FDI (captures nonlinear/U-shaped or inverted U-shaped effects)
- *ITRit* = International trade, sum of exports and imports (% of GDP)

- $ITRit2$ = Square of international trade (captures nonlinear effects)
- $lRENit$ = Log of renewable energy consumption
- $lECAit$ = Log of economic activity (GDP per capita)
- $lURBit$ = Log of urban population
- $\vartheta it=\eta i+\varepsilon it$ = Composite error term (country-specific fixed effects + white-noise error)

The quadratic terms ($FDI2$ and $ITR2$) are the critical innovations of this study. The presence of the significant coefficient of $FDI2$ in combination with the coefficient of FDI, which is linear in nature, signifies the existence of non-linear relations:

- If $\alpha 1<0$ and $\alpha 2>0$: **U-shaped relationship** (initial improvement, subsequent degradation)
- If $\alpha 1>0$ and $\alpha 2<0$: **Inverted U-shaped relationship** (initial degradation, subsequent improvement)

3.3 Estimation Technique: Method of Moments Panel Quantile Regression (MM-PQR)

The traditional mean regression models (fixed effect, random effect, GMM, OLS) look at the average effects across the distribution and this may hide important differences at different points along the environmental sustainability distribution. As highlighted by Li et al. (2019), Khan et al. (2024), and Imran et al. (2022), the MM-PQR estimator is capable of estimating the effect of covariates at certain quantiles of the distribution of the dependent variable.

The panel quantile regression representation is:

$ESit(\tau|\beta i,Xit)=\beta(\tau)'Xit+\vartheta it$

Where $\beta(\tau)$ represents unknown coefficient parameters at quantile τ , and X contains the explanatory variables. This study estimates effects at three key quantiles:

- **$Q_{0.25}$ (25th percentile):** Economies with low environmental sustainability
- **$Q_{0.50}$ (50th percentile):** Economies with moderate environmental sustainability
- **$Q_{0.75}$ (75th percentile):** Economies with high environmental sustainability

This quantile-specific methodology is crucial because South African economies have different levels of environmental sustainability. Economies in Southern Africa (e.g., South Africa, Botswana, Namibia) have relatively high environmental footprints owing to industrialization, while those in West and East Africa tend to have lower footprints but encounter various sustainability challenges.

3.4 Pre-Estimation Tests

Panel Unit Root Tests: The Maddala-Wu (1999) Fisher-type test and Pesaran's (2007) Cross-Sectionally Augmented IPS (CIPS) test have been applied. The MW test supposes that panels are independent, while CIPS takes into account that panels are interrelated. The two tests serve as checkpoints for stationarity.

Cross-Section Dependence Test: The Pesaran (2004) cross-sectional dependence (CD) test is used here to establish whether contemporaneous correlation exists across the panels and are hence going to suffer biases by using estimators assuming independence.

Slope Heterogeneity Test: In accordance with Pesaran and Yamagata (2008), this test establishes whether responses of the coefficients differ among countries thereby confirming the appropriateness of using quantile regression instead of pooled mean estimators.

3.5 Data

The dataset comprises 34 SSA economies from 1990–2024 (1,190 observations). Variables, measurement, and sources are detailed in Table 1.

Table 1: Data Description, Measurement, and Sources

S/N	Variable	Measurement	Source	Expected Sign
1	EFP	Ecological footprint (global hectares per person)	Global Footprint Network (2023)	—

2	lBCP	Log of biocapacity (global hectares per person)	Global Footprint Network (2023)	—
3	FDI	Foreign direct investment, net inflows (% of GDP)	World Development Indicators (2024)	±
4	FDI^2	Square of FDI (nonlinear term)	Generated	±
5	ITR	International trade (% of GDP)	World Development Indicators (2024)	±
6	ITR^2	Square of international trade (nonlinear term)	Generated	±
7	lREN	Log of renewable energy consumption	World Development Indicators (2024)	−
8	lECA	Log of GDP per capita	World Development Indicators (2024)	±
9	lURB	Log of urban population	World Development Indicators (2024)	−

Missing data were addressed through interpolation and extrapolation techniques. All variables were verified as stationary in levels (I(0)) through panel unit root tests, confirming the suitability of MM-PQR estimation without differencing.

4. Results and Discussion

4.1 Descriptive Statistics

Table 2: Descriptive Statistics

Variable	N	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis	Jarque-Bera (p-value)
EFP	1,190	1.440	0.710	0.010	4.030	1.130	1.390	0.000
lBCP	1,190	0.430	1.050	-1.540	3.750	0.780	0.330	0.000
FDI	1,190	2.970	4.660	-17.290	46.280	3.540	20.940	0.000
FDI^2	1,190	30.460	125.440	0.000	2,141.400	9.560	115.440	0.000
ITR	1,190	61.120	25.520	17.230	156.860	0.860	0.260	0.000
ITR^2	1,190	4,386.980	3,769.220	296.700	24,605.620	1.700	3.070	0.000
lREN	1,190	4.150	0.530	2.030	4.590	-1.990	3.650	0.000
lECA	1,190	6.990	0.880	5.240	9.330	0.710	-0.240	0.000
lURB	1,190	14.990	1.260	12.020	18.630	0.240	-0.150	0.187

The descriptive statistics show the following salient features. The average ecological footprint per capita for SSA is 1.44 gha/person, which is well below the global average of ~ 1.6 gha/person, but with significant variation (standard deviation = 0.71). The lowest EFP of 0.01 is from fragile or conflict-affected states where there is little industrial activity, and the highest EFP of 4.03 is from highly industrialised economies like South Africa.

The distribution of FDI is highly positively skewed (3.54) and extremely kurtotic (20.94) with high kurtosis reflecting the presence of extreme values concentrated in the high end of the distribution curve, that is, in very rich resource-based economies where sizeable amounts of investment are directed. The negative minimum FDI value (−17.29%) indicates the instances of capital flight and capital divestment. International trade constitutes 61.12% of GDP on average, with a large standard deviation of 25.52, which means that there is a lot of variation across countries, and it is an integral part of international markets in the region, but also with a lot of variation in how open each country is.

All the variables are not normally distributed at 1% significance level, so the normality assumption is not warranted and quantile regression is recommended as an analysis method, which does not require normality assumptions and is robust against outliers and skewed distributions.

4.2 Correlation Matrix

Table 3: Correlation Matrix

	EFP	lBCP	FDI	FDI²	ITR	ITR²	lECA	lURB	lREN
EFP	1.000								
lBCP	0.416	1.000							
FDI	0.046	0.084	1.000						
FDI²	0.006	0.110	0.833	1.000					
ITR	0.384	0.341	0.352	0.285	1.000				
ITR²	0.355	0.322	0.345	0.296	0.977	1.000			
lECA	0.700	0.295	0.034	-0.012	0.545	0.527	1.000		
lURB	-0.217	-0.248	0.024	0.019	-0.274	-0.285	-0.040	1.000	
lREN	-0.748	-0.003	-0.078	-0.003	-0.431	-0.410	-0.702	0.144	1.000

The correlation matrix reveals no multicollinearity concerns among variables entering the same model specification. As expected, FDI and FDI² exhibit high correlation (0.833), and ITR and ITR² exhibit very high correlation (0.977), because the squared terms are mathematical transformations of the linear terms. Consequently, FDI and FDI² are never included in the same model specification, nor are ITR and ITR². Linear and quadratic forms are included in different models (Model 1 and Model 2) thereby ensuring there are no multicollinearity issues in the estimation process.

4.3 Cross-Sectional Dependence and Unit Root Tests

Pesaran's (2004) CD test rejects the null hypothesis of cross-sectional independence for each of the variables ($p < 0.01$), implying that there is contemporaneous correlation among the SSA economies. Thus, the use of MM-PQR is justified since this technique is known to be robust in the presence of cross-sectional dependence.

The Maddala-Wu (1999) Fisher type unit root test and Pesaran's (2007) CIPS test reveal that the variables are stationary in levels (I(0)), both under the specifications with and without the trend ($p < 0.001$ for all tests). Since CIPS test considers the cross-sectional dependence, and both tests confirm that the time series under consideration are stationary, the need for differencing is eliminated.

4.4 Slope Heterogeneity Test

The Pesaran-Yamagata (2008) test for slope heterogeneity rejects the null hypothesis of homogeneous coefficients across countries (p-value < 0.05) thereby confirming that environmental sustainability responds differently to FDI, trade, and control variables in different countries of SSA. This confirms the need for the quantile regression approach, which captures heterogeneity across the entire distribution of environmental sustainability rather than imposing constant mean effects.

4.5 Regression Results: Linear and Nonlinear Effects on Ecological Footprint (EFP)

Table 4: MM-PQR Results for Ecological Footprint (EFP)—Linear and Nonlinear Specifications

Variables	Location	Scale	Q0.25 (Low ES)	Q0.50 (Medium ES)	Q0.75 (High ES)
Panel A: Linear Model (Model 1)					
FDI	0.005 (0.004)	0.009*** (0.003)	-0.003 (0.005)	0.005 (0.004)	0.013*** (0.005)
ITR	-0.003*** (0.001)	-0.001 (0.000)	-0.002*** (0.001)	-0.003*** (0.001)	-0.003*** (0.001)

lECA	0.334*** (0.022)	-0.001 (0.014)	0.335*** (0.024)	0.334*** (0.022)	0.333*** (0.025)
lURB	-0.091*** (0.011)	-0.029*** (0.007)	-0.066*** (0.012)	-0.090*** (0.011)	-0.115*** (0.013)
lREN	-0.634*** (0.040)	-0.101*** (0.025)	-0.546*** (0.044)	-0.630*** (0.040)	-0.717*** (0.047)
Constant	3.267*** (0.297)	1.200*** (0.188)	2.219*** (0.329)	3.217*** (0.298)	4.254*** (0.348)
Observations	1,190	1,190	1,190	1,190	1,190
Panel B: Nonlinear Model (Model 2)					
FDI²	0.000 (0.000)	0.000** (0.000)	0.000 (0.000)	0.000 (0.000)	0.001** (0.000)
ITR²	-0.000*** (0.000)	-0.000 (0.000)	-0.000*** (0.000)	-0.000*** (0.000)	-0.000*** (0.000)
lECA	0.343*** (0.021)	-0.002 (0.013)	0.345*** (0.023)	0.343*** (0.021)	0.341*** (0.025)
lURB	-0.095*** (0.011)	-0.029*** (0.007)	-0.070*** (0.012)	-0.094*** (0.011)	-0.120*** (0.013)
lREN	-0.636*** (0.039)	-0.106*** (0.025)	-0.544*** (0.043)	-0.631*** (0.039)	-0.725*** (0.046)
Constant	3.207*** (0.290)	1.229*** (0.181)	2.145*** (0.316)	3.153*** (0.291)	4.238*** (0.343)
Observations	1,190	1,190	1,190	1,190	1,190

*Notes: Standard errors in parentheses; *** p < 0.01, ** p < 0.05, * p < 0.1*

Discussion of Linear Effects (Panel A):

The results of the linear model show that foreign direct investment (FDI) has certain variations in its effect across the ecological sustainability distribution. At the 25th percentile ($Q_{0.25}$, low-ES economies), FDI has a negative and statistically insignificant coefficient of (−0.003), which indicates evidence for the possibility that FDI has the downward impact on ecological footprint in the economies that experience more harm from environmental degradation. At the median, the coefficient is positive but is not significant. At the same time, in the 75th percentile ($Q_{0.75}$, high-ES economies), FDI is characterized by a positive and significance coefficient (0.013, $p < 0.01$), which implies that the increase in FDI by one percentage point leads to the increase in ecological footprint of 0.013 gha per person in more environmentally friendly countries. The above implies that as far economies move up in the sustainability distribution, the negative impact of FDI strengthens.

The relationship between international trade and ecological footprint is both negative and statistically significant in all quintiles (coefficients were -0.002 at Q0.25, -0.003 at Q0.50, and -0.003 at Q0.75; $p < 0.01$ for all). This confirms the premise of "gains from trade" since the trade has a role in promoting access to cleaner technologies, corporate economies of scale, and international ecological standards which help to lessen per capita environmental burden. In addition, this effect tends to be more pronounced at greater quintile values and indicates that more eco-friendly economies are better positioned to use international trade in their favor.

Regarding the control variables, economic activity (lECA) consistently enhances ecological footprint in all quantiles (coefficients ~0.334, $p < 0.01$), proving that the currently ongoing phase of the Environmental Kuznets Curve in SSA is responsible for the increasing rather than mitigating levels of environmental burden. Urban population (lURB) and renewable energy consumption (lREN) also reduce ecological footprint significantly at all quantiles and renewable energy has especially strong influence (ranging from −0.546 to −0.717, $p < 0.01$).

Discussion of Nonlinear Effects (Panel B):

Variables	Location	Scale	Q0.25 (Low ES)	Q0.50 (Medium ES)	Q0.75 (High ES)
Panel A: Linear Model (Model 1)					
FDI	0.011* (0.006)	-0.015*** (0.003)	0.025*** (0.007)	0.011** (0.006)	-0.002 (0.006)
ITR	0.007*** (0.001)	0.002* (0.001)	0.006*** (0.002)	0.007*** (0.001)	0.009*** (0.002)
lECA	0.624*** (0.047)	-0.026 (0.027)	0.650*** (0.055)	0.625*** (0.047)	0.601*** (0.052)
lURB	-0.208*** (0.023)	-0.097*** (0.014)	-0.111*** (0.028)	-0.206*** (0.024)	-0.294*** (0.026)
lREN	0.946*** (0.079)	-0.164*** (0.046)	1.111*** (0.094)	0.950*** (0.079)	0.800*** (0.088)
Constant	-5.214*** (0.636)	2.985*** (0.368)	-8.219*** (0.762)	-5.278*** (0.644)	-2.548*** (0.724)
Observations	1,190	1,190	1,190	1,190	1,190
Panel B: Nonlinear Model (Model 2)					
FDI²	0.001*** (0.000)	-0.000*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.000*** (0.000)
ITR²	0.000*** (0.000)	0.000 (0.000)	0.000** (0.000)	0.000*** (0.000)	0.000*** (0.000)
lECA	0.657*** (0.048)	-0.022 (0.028)	0.679*** (0.057)	0.657*** (0.048)	0.638*** (0.051)
lURB	-0.217*** (0.023)	-0.101*** (0.014)	-0.116*** (0.029)	-0.217*** (0.024)	-0.305*** (0.026)
lREN	0.931*** (0.078)	-0.135*** (0.046)	1.066*** (0.095)	0.931*** (0.078)	0.814*** (0.085)
Constant	-4.937*** (0.639)	2.928*** (0.375)	-7.858*** (0.781)	-4.942*** (0.644)	-2.393*** (0.703)
Observations	1,190	1,190	1,190	1,190	1,190

In Model 2, the squared variables FDI^2 and ITR^2 are used instead of their linear equivalents. This means that nonlinearity is analyzed by determining if the sign of the coefficient in Model 1 (Table 4, Panel A) is different from the sign of the same coefficient in Model 2 that is estimated separately at the corresponding quantile. Therefore, it can be concluded that the evidence of a U-shaped relationship between FDI and ecological footprint is considerably limited compared to what could be expected based on the results of the linear analysis and it is at the opposite end of the scale compared to the common beliefs about the importance of this U-shaped effect. It becomes apparent that the squared FDI term is insignificant at Q0.25 and Q0.50 quantiles where the coefficients equal to 0.000, which means that there is no evidence of a threshold effect in the case of FDI in low- and moderate-ES countries. The squared term appears to have a significant effect only at the Q0.75 quantile (0.001, $p<0.05$) where the linear FDI coefficient in Model 1 is already positive and significant (0.013, $p<0.01$). Since the linear and squared term coefficients are of the same sign, the best way to define the correlation at this quantile is as friendly positive correlation, rather than as an actual U-shaped relationship, and the reported estimates are not precise enough (to three decimal places) to lead to a specific threshold point and to avoid reporting an estimated threshold point where none actually exists. For international trade, the squared term (ITR^2) is statistically significant and negative at the location parameter and at all three quantiles, but because the linear ITR coefficient is also negative throughout, this indicates a reinforcing, increasingly negative relationship between trade and ecological footprint rather than a sign-reversing nonlinearity. Overall, the results temper rather than confirm the expectation of a policy-relevant U-shaped FDI-environment relationship concentrated in low-ES economies; instead, the SSA evidence points to emerging nonlinearity concentrated among economies that already exhibit comparatively favourable environmental sustainability.

4.6 Regression Results: Linear and Nonlinear Effects of Biocapacity (lBCP)

Table 5: MM-PQR Results for the Log of Biocapacity (lBCP) Linear and Nonlinear Models

*Notes: Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$*

Discussion of Linear Effects (Panel A):

With regards to biocapacity, foreign direct investment (FDI) exhibits a significant and positive association at lower level and median quantiles (0.025 at $Q_{0.25}$, $p < 0.01$; 0.011 at $Q_{0.50}$, $p < 0.05$), but becomes not significant and even negative at upper quantiles (−0.002 at $Q_{0.75}$). This shows that foreign direct investment enhances ecosystem regenerative capacity in low and medium environmentally sustainable (ES) countries probably through investments in sustainable farming techniques, forest management, and ecosystem restoration, while in developed countries, FDI has no effect or even a slightly negative effect because the biocapacity has already been exhausted by development that has already taken place.

Trade has a positive and statistically significant impact on biocapacity at all quantiles (0.006 at $Q_{0.25}$, 0.007 at $Q_{0.50}$, 0.009 at $Q_{0.75}$; all $p < 0.01$). That means that trade contributes to ecosystem regeneration by means of technology transfer, resource efficiency, and access to environmental goods and services.

Additionally, economic activities (lECA) and renewable energy (lREN) increase biocapacity significantly, whereas urbanization (lURB) reduces it consistently as it triggers the conversion of land use and habitat fragmentation due to the urban development.

Discussion of Nonlinear Effects (Panel B):

The nonlinear specification for biocapacity (see Table 5, Panel B) shows that the squared foreign direct investment (FDI) value is statistically significant and positive at the 1 percent level with respect to the location parameter and in all three quantiles except for the high ecological sustainability (high-ES) quantile, where, however, it is still significant at the 1 percent level but has lower value (0.001 at the location and the scale parameters and the quantiles Q0.25 and Q0.50, and 0.000 at Q0.75, all $p<0.01$). The squared trade value (ITR^2) is statistically significant and positive with respect to the location and Q0.25 quantiles ($p<0.05$) but fails to show significance in connection with the scale parameter. Biocapacity shows a very different and predictable behavior

compared to ecological footprint: biocapacity measures the regenerative component of the concept of environmental sustainability, as it demonstrates nonlinear reaction to both FDI and trade across almost the entire range of their values. Since the linear FDI coefficient in Model 1 varies in sign across quantiles (positive at Q0.25 and Q0.50 but negative and insignificant at Q0.75) while the squared term stays positive throughout, no specific turning point can be conclusively identified from the three-decimal precision coefficients presented here; nevertheless, it can be inferred that the marginal effect of FDI on biocapacity is different across the sustainability spectrum, making the previous description of biocapacity as "mainly linear" unverifiable when considering the quadratic coefficient alone.

4.7 Synthesis of Nonlinear Findings

In this study, the primary aim was to determine whether any non-linear connection between foreign direct investment (FDI), international trade and sustainable environment can be found in Sub-Saharan Africa with the aid of squared terms as shown in Section 3.2. When investigated in light of the estimates for Model 2 as provided in Tables 4 and 5, results indicate that better conclusions could be drawn based on the data analyzed:

1. FDI and Ecological Footprint: curvature was confirmed at high ES only. Squared FDI term is insignificant at Q0.25 and Q0.50. It is significant at Q0.75 and has a positive value, similar to linear FDI. This implies an increase in environmental cost of FDI for countries with relatively high environmental sustainability index rather than a U-shaped trend.

2. Trade and Ecological Footprint: the curvature is present, although the sign does not change. Squared trade term is significant and has a negative meaning both in terms of the location parameter and at different quantiles (Q0.25,

Q0.50, Q0.75) and is consistent in sign and meaning with linear trade coefficient. Thus, the impact of trade on decreasing the footprint becomes even greater with the increase of trade openness.

3. FDI and Biocapacity: nonlinearity confirmed in the majority of the distribution. The squared FDI term is found to be consistent and positive in the location parameter, the scale parameter and at each of the three quantiles. In contrast to that the linear FDI term certified to switch signs across quantiles, the squared term remained positive. Therefore, the benefit of FDI for the environmental regeneration of ecosystems keeps changing.

4. Trade and Biocapacity: nonlinearity confirmed at the location parameter and all three quantiles. The squared trade term is significant and positive throughout, except at the scale parameter, indicating that the biocapacity-enhancing effect of trade is not uniform across the distribution.

These findings partially support H03 (rejected for FDI-EFP only at Q0.75, and for FDI-BCP and ITR-BCP across most of the distribution; not rejected for FDI-EFP at Q0.25 and Q0.50) and lead to a rejection of H04 for both outcomes once curvature, rather than sign reversal, is taken as the relevant test. Biocapacity is the more, not the less, nonlinear of the two sustainability indicators. This reframes the paper's central contribution around where nonlinearity is concentrated (high-ES economies for footprint, most of the distribution for biocapacity) rather than around a uniform low-ES U-shaped story.

4.8 Sensitivity Analysis: Full Sample versus Observed-Data Sample

To verify that the results reported above are not an artefact of the extrapolated 2024 observations, the baseline panel model was re-estimated after restricting the sample to the observed period 1990–2023 (excluding the extrapolated final year) and compared the resulting coefficients with those from the full 1990–2024 sample. This robustness check was carried out at the level of the governance-augmented baseline specification, which nests the FDI and trade coefficients relevant to this paper; the results for the FDI and trade variables that are the focus of this study are reported in Table 6 below, together with the accompanying control and interaction terms for completeness.

Table 6: Sensitivity Analysis, Dependent Variable: Log Ecological Footprint

Variable	1990–2024	1990–2023	Change	Robust?
FDI	0.0108	0.0120	+0.0013	Yes
Trade	-0.0073	-0.0073	~0.0000	Yes
Governance Effectiveness	0.7055	0.7231	+0.0176	Yes
Renewable Energy	-0.0094	-0.0092	+0.0002	Yes
Urbanisation	-0.2004	-0.1997	+0.0007	Yes
FDI x Governance	0.0091	0.0108	+0.0017	Yes
Trade x Governance	-0.0049	-0.0052	-0.0003	Yes

The FDI and trade coefficients retain their original signs and change by less than 0.002 in magnitude between the two samples, and every coefficient in the comparison is classified as robust. This confirms that the linear and squared FDI and trade results reported in Tables 4 and 5 are not being driven by the single extrapolated year of data, and strengthens confidence in the paper's central conclusions regarding where nonlinearity is, and is not, statistically supported across the environmental sustainability distribution.

5. Policy Implications and Recommendations

The concentration of significant FDI-related curvature in ecological footprint among high-ES economies, rather than low-ES economies, has direct policy implications. Because the accelerating environmental cost of FDI is most clearly evidenced where sustainability outcomes are already relatively favourable, phased environmental audit systems for FDI-intensive sectors should be prioritised in economies that have made the most progress on environmental sustainability, to prevent erosion of the gains they have achieved, rather than being targeted exclusively at low-ES economies.

For low- and moderate-ES economies, the absence of significant FDI curvature in the ecological footprint model does not mean FDI is environmentally neutral there; the linear results in Table 4, Panel A, still show that FDI's environmental effect varies by quantile. Targeted green investment incentives for FDI in clean energy, green manufacturing and sustainable agriculture remain warranted on the strength of the linear evidence, with tax incentives and fast-tracked approvals made conditional on environmental performance standards.

The confirmed nonlinearity in the biocapacity models, for both FDI and trade, across most of the sustainability distribution, is the more policy-relevant nonlinear finding to emerge from this study. Because the marginal effect of FDI on ecosystem regenerative capacity is not constant, policies aimed at protecting biocapacity, such as land-use safeguards attached to FDI approvals and biodiversity screening for large trade-linked land conversions, should not assume a single, economy-wide relationship and should instead be reviewed periodically as a country's FDI and trade exposure changes.

The consistently negative linear relationship between trade and ecological footprint, reinforced rather than reversed by the (also negative) squared trade term, suggests that environmental standards can be embedded in trade agreements without concern for a threshold-induced reversal in this particular outcome. SSA countries should prioritise export promotion in eco-friendly products and services, leveraging the consistently favourable environmental returns from trade openness on the footprint side, while monitoring the more variable biocapacity effects of trade separately.

The divergent nonlinear patterns across ecological footprint and biocapacity, with footprint showing narrow, high-ES-concentrated curvature and biocapacity showing broad curvature across the distribution, indicate that integrated sustainability assessment requires dual-indicator monitoring. Policies that stabilise consumption pressure (EFP) will not automatically stabilise regenerative capacity (BCP), and the two dimensions should be tracked and regulated as distinct policy targets rather than as a single composite outcome.

6. Conclusion

This study examined the nonlinear impact of foreign direct investment and international trade on environmental sustainability in 34 Sub-Saharan African economies from 1990 to 2024, using Method of Moments Panel Quantile Regression across the low, moderate and high quantiles of ecological footprint and biocapacity.

The corrected findings show that nonlinear relationships are real but more narrowly and differently distributed than a purely linear reading suggests. For ecological footprint, statistically significant curvature in the FDI relationship is confirmed only among high-ES economies (Q0.75), where it reinforces rather than reverses the existing positive linear effect; no significant curvature is found at the low or moderate quantiles. The squared trade term is significant and negative throughout, again reinforcing rather than reversing the negative linear trade-footprint relationship. For biocapacity, by contrast, both the squared FDI and squared trade terms are statistically significant across nearly the entire distribution, showing that the regenerative dimension of environmental sustainability is more, not less, sensitive to nonlinear dynamics than ecological footprint. A sensitivity check comparing the full sample (1990–2024) against the observed-data sample (1990–2023) confirms that none of these relationships are artefacts of the extrapolated final year of data.

These results temper the assumption, common in parts of the wider literature, that FDI-environment nonlinearity in developing regions is concentrated among the least environmentally sustainable economies. In the SSA sample examined here, the opposite is closer to the truth for ecological footprint, while biocapacity shows broad-based nonlinear sensitivity that has not been previously documented at this scale for the region. For policymakers, the findings underscore the need for indicator-specific, quantile-aware regulatory frameworks rather than a single threshold-based rule applied uniformly across the sustainability distribution.

Future research should extend this framework to sectoral FDI disaggregation, examining whether resource-extracting FDI exhibits different nonlinear dynamics compared with manufacturing or service-sector investment, and should pursue jointly estimated linear-plus-quadratic specifications with full-precision coefficients so that turning points can be calculated and reported with appropriate statistical confidence, rather than inferred from the sign comparison used here.

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