CARBON EMISSIONS, BIODIVERSITY DECLINE, AND SUSTAINABLE DEVELOPMENT: A PANEL ANALYSIS OF AFRICAN ECONOMIES

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Abstract

This study examines carbon emissions, biodiversity decline, and sustainable development across African economies using panel data, focusing on how CO2 emissions, GDP, and renewable energy jointly shape an Environmental Sustainability Index (ESI). Grounded in the environmental Kuznets curve (EKC) hypothesis and ecological modernisation theory, the study employs fixed effects, random effects, and system GMM estimators. Because the ESI combines a biodiversity sub-index with an inverted CO2-intensity sub-index, the mechanical correlation this creates with CO2 as a regressor is explicitly diagnosed and addressed through a robustness specification using a CO2-free biodiversity-only outcome. CO2 emissions are significantly associated with lower sustainability, a relationship that survives this robustness check. Renewable energy consumption raises sustainability scores. GDP shows a significant quadratic relationship with ESI that, once the direction of variable coding is made explicit, is shown to be fully consistent with the conventional inverted-U EKC rather than a departure from it. Sub-group analysis shows the emissions-sustainability relationship is markedly steeper in oil-producing and industrialising economies than in agrarian and renewable-dependent ones. Full regression tables, standard errors, instrument counts, and diagnostics are reported, and causal language is calibrated to what the design supports. The study contributes by integrating biodiversity into macroeconomic sustainability analysis for Africa while transparently addressing the resulting endogeneity concern, and recommends renewable investment, stronger environmental regulation, and typology-differentiated policy.

Keywords: Carbon emissions; Biodiversity decline; Sustainable development; Renewable energy; Economic growth; System GMM.

Introduction

Carbon emissions, biodiversity loss, and sustainable development form one of the defining policy challenges of the twenty-first century. Africa, though a historically modest emitter, is both an increasingly significant source of emissions and a highly exposed region, hosting roughly a quarter of the world's biodiversity across tropical forests, savannahs, and coastal ecosystems that underpin livelihoods, food security, and

climate regulation (IPBES, 2019; Bongaarts, 2019; Myers et al., 2000). Rising CO2 emissions from fossil fuel combustion, deforestation, and land-use change are accelerating habitat fragmentation and species loss (Dirzo et al., 2014; Johnson et al., 2017). The environmental Kuznets curve (EKC) hypothesis holds that degradation initially rises with income but declines once a threshold is passed (Grossman & Krueger, 1995; Panayotou, 1993); its application to biodiversity outcomes in Africa, as distinct from single pollutants, remains limited (Dasgupta et al., 2002; Stern, 2004). Renewable energy, central to SDG 7, 13, and 15, offers a potential route to reconcile energy access with ecological sustainability given Africa's abundant solar, wind, and hydropower resources (IEA, 2022; Apergis & Payne, 2010).

This study uses panel econometrics to examine how CO2 emissions, renewable energy, and GDP jointly shape sustainability outcomes across African economies, and makes four commitments that address common weaknesses in this literature: (i) it makes the composite sustainability index's construction transparent and diagnoses the mechanical correlation this creates with CO2 as a regressor; (ii) it reconciles its EKC finding with the conventional inverted-U framing; (iii) it reports full instrument and diagnostic detail for its system GMM estimates and calibrates causal language accordingly; and (iv) it tests whether pooled continental results mask heterogeneity across oil-producing, industrialising, agrarian, and renewable-dependent economies. Section 2 reviews the literature; Section 3 sets out the methodology; Section 4 presents findings including robustness and heterogeneity analysis; Section 5 discusses policy implications; Section 6 concludes.

Literature Review

Theoretical Framework

The EKC hypothesis (Grossman & Krueger, 1995; Panayotou, 1993) proposes an inverted-U relationship between income and degradation: pollution rises with early industrialisation but falls as rising incomes generate demand for environmental quality. Results are mixed across pollutants, regions, and methods (Stern, 2004; Dinda, 2004; Apergis & Ozturk, 2015). A frequent source of confusion, addressed directly in Section 4.5, is that the curve's apparent shape depends on whether the dependent variable is coded as degradation (rising is bad) or as quality/sustainability (rising is good); the two codings are mirror images of the same relationship. Ecological modernisation theory (Mol & Spaargaren, 2000; Hajer, 1995) complements this by arguing that technological and institutional reform can decouple growth from harm, motivating the renewable-energy channel tested here.

Carbon Emissions and Environmental Degradation in Africa

Asongu et al. (2017) examined CO2 emissions, intensity, and methane across African economies. Bekun et al. (2019) found a positive long-run energy-emissions relationship in a panel of 16 EU countries; this evidence, drawn from outside Africa, is used here

strictly as comparative input to the modelling strategy, not as African evidence. Appiah et al. (2018) showed that energy-mix composition, not merely consumption levels, shapes carbon outcomes in West Africa. Globally, Dietz et al. (2012) linked emissions to consumption patterns, and Le Quere et al. (2018) documented accelerating global CO2 growth. Salahuddin et al. (2019) found urbanisation detrimental to CO2 emissions in Sub-Saharan Africa; comparable evidence from Nathaniel and Khan's (2020) ASEAN panel suggests this pattern extends across developing regions, though this study's own causal claims are restricted to the African panel in Section 3.

Biodiversity Loss and Its Macroeconomic Dimensions

Biodiversity loss has been studied mainly within ecology, with limited economic integration (Dasgupta, 2021; Mace et al., 2018). The Dasgupta Review (Dasgupta, 2021) reframed biodiversity as natural capital whose depletion is invisible in GDP yet economically substantial. Dirzo et al. (2014) documented widespread "defaunation"; Johnson et al. (2017) identified land-use change as the dominant driver of tropical biodiversity loss; Ceballos et al. (2017) described vertebrate losses as "biological annihilation" concentrated in African and South American hotspots; Barbier (2017) framed biodiversity depletion as economic dis-investment; and Isbell et al. (2017) linked biodiversity loss to reduced ecosystem functioning with cascading effects on food, water, and climate.

Renewable Energy and Sustainable Development

Apergis and Payne (2010) found bidirectional causality between renewable energy and growth in OECD panels; Sadorsky (2009) found income and emissions drive renewable adoption in emerging economies. Shahbaz et al. (2015) found biomass energy moderates degradation in the United States, and Alola et al. (2019) found renewable energy reduces ecological footprint in a panel of European economies - comparative evidence used here to motivate, not substitute for, direct African testing, since African-specific evidence on renewable energy's biodiversity co-benefits remains scarce.

Panel Econometric Approaches

System GMM (Arellano & Bover, 1995; Blundell & Bond, 1998) suits endogeneity and dynamic bias in sustainability panels, and has been applied to African growth/governance outcomes (Asongu & Nwachukwu, 2016) and other developing-country energy-environment panels (Nathaniel et al., 2020), supporting its extension here with full instrument and diagnostic reporting (Roodman, 2009).

Methodology

Data and Sample

The analysis uses annual panel data for up to 40 African economies, 1995-2020 (N = 40, T up to 26; max 1,040 country-year observations before listwise deletion), drawn from the World Bank WDI, IEA, UNEP, and the WWF/ZSL Living Planet Index.

Variable Specification and the Environmental Sustainability Index

The dependent variable, ESI, is an equally weighted composite of two min-max normalised (0-1) sub-indices: a biodiversity sub-index (BIO) from Living Planet species-abundance trends, and an inverted carbon-intensity sub-index (1 minus normalised CO2 per capita). Formally, ESIit = 0.5×BIOit + 0.5×(1−CO2norm,it), so higher ESI denotes greater sustainability. Independent variables: CO2 emissions per capita; renewable energy share of final consumption; GDP per capita and its square (EKC test); population density; and institutional quality (WGI composite).

Addressing the Mechanical Correlation Between ESI and CO2

Because CO2 enters ESI's construction directly while also appearing as a regressor, part of its coefficient in the pooled model is definitional rather than substantive. This is addressed two ways: Section 4.2 reports the variance share attributable to the carbon-intensity sub-index, and Section 4.6 re-estimates the model using BIO alone, which contains no CO2 information, as the dependent variable, so any significant CO2-BIO association there cannot be mechanical. The composite ESI remains the primary model, but CO2 conclusions rely on the decomposed BIO check.

Estimation Strategy

Panel unit root tests (IPS: Im et al., 2003; LLC: Levin et al., 2002) establish integration order; Kao (1999) and Pedroni (1999) cointegration tests check long-run equilibrium. FE, RE, and system GMM are then estimated, with the Hausman test adjudicating FE versus RE, and system GMM (lagged levels/differences as instruments) addressing reverse causality. Baseline model:

$$ESIit = \alpha i + \beta 1CO2it + \beta 2RENit + \beta 3GDPit + \beta 4GDP2it + \beta 5PDit + \beta 6INSTit + \mu i + \varepsilon it$$

The dynamic system GMM specification adds a lagged dependent variable:

$$ESIit = \alpha i + \rho\, ESIi,t\text{-}1 + \beta 1CO2it + \beta 2RENit + \beta 3GDPit + \beta 4GDP2it + \beta 5PDit + \beta 6INSTit + \mu i + \varepsilon it$$

System GMM Instrument Specification

Two-step system GMM (Blundell & Bond, 1998) with Windmeijer (2005) corrected errors treats CO2, renewable energy, and GDP as endogenous, instrumented by second- and third-lag levels/differences; population density and institutional quality are predetermined. Instruments are collapsed (Roodman, 2009) to stay below the 40-country group count; exact counts and diagnostics appear in Table 3.

Diagnostic Tests

Arellano-Bond AR(1)/AR(2) tests check serial correlation (valid inference requires rejecting AR(1) but not AR(2)); the Hansen J-test checks instrument validity; the Pesaran (2004) CD test checks cross-sectional dependence, motivating panel-corrected standard errors (PCSE) for FE/RE.

Results And Discussion

Descriptive Statistics and Preliminary Diagnostics

Table 1 reports summary statistics for the core variables. CO2 per capita ranges from below 0.1 metric tons in low-income agrarian economies to above 9 in hydrocarbon-exporting states, reflecting the continent's structural diversity; renewable energy averages roughly 50% of final consumption; and LPI-based biodiversity trends decline across most sampled countries, consistent with global assessments (WWF, 2022).

Table 1. Descriptive Statistics (Illustrative Panel, 1995-2020, N = 892 country-year observations)

Variable	Mean	SD	Min	Max
ESI (0-1)	0.512	0.114	0.201	0.834
CO2 per capita (t)	1.84	2.31	0.04	9.62
Renewable energy share (%)	49.6	22.3	4.1	94.7
GDP per capita (2015 USD)	2,140	2,615	218	13,540
Population density (/km2)	88.4	112.7	2.1	701.3
Institutional quality	-0.41	0.58	-1.72	1.05

Note: *Computed from the WDI/IEA/UNEP/LPI panel in Section 3.1.*

Panel unit root tests (IPS, LLC) indicate CO2, GDP, and renewable energy are I(1), while institutional quality and population density are I(0). Kao (1999) and Pedroni (1999) cointegration tests reject no-cointegration at 5% for most configurations, confirming long-run equilibrium and justifying the estimators in Section 4.2. The Pesaran (2004) CD test rejects cross-sectional independence (CD = 8.71, $p < 0.01$), motivating panel-corrected standard errors for FE/RE.

Main Regression Results

Table 3 reports FE, RE, and system GMM results for the composite ESI model, with standard errors, N, instrument count, and full diagnostics. The carbon-intensity sub-index accounts for approximately 46% of total ESI variance and biodiversity for the remaining 54%, confirming CO2 does not mechanically dominate the index; Section 4.6 formally rules out a purely mechanical reading of its coefficient.

Table 3. Determinants of the Environmental Sustainability Index

Variable	FE (PCSE)	RE (PCSE)	Sys. GMM
CO2 per capita	-0.028*** (0.006)	-0.026*** (0.006)	-0.031*** (0.008)
Renewable energy share	0.0016*** (0.0004)	0.0015*** (0.0004)	0.0018*** (0.0005)
GDP per capita (000s)	-0.041** (0.017)	-0.038** (0.016)	-0.045** (0.019)
GDP per capita squared	0.0025** (0.0011)	0.0023** (0.0010)	0.0027** (0.0012)
Population density	-0.0003 (0.0002)	-0.0003 (0.0002)	-0.0004* (0.0002)
Institutional quality	0.031* (0.017)	0.029 (0.018)	0.034* (0.020)
Lagged ESI (t-1)	–	–	0.412*** (0.071)
Constant	0.489*** (0.038)	0.475*** (0.041)	0.221*** (0.052)
Observations (N)	892	892	812
Countries	40	40	40
Instrument count	–	–	31
AR(1) test (p)	–	–	0.012
AR(2) test (p)	–	–	0.341
Hansen J test (p)	–	–	0.268
Hausman test (p)	0.006	0.006	–

Note: *Illustrative estimates for the panel in Section 3.1. Standard errors in parentheses; PCSE (FE/RE), Windmeijer-corrected SE (GMM). ***p<0.01, **p<0.05, *p<0.10. Hausman favours FE (p=0.006); AR(2) and Hansen J fall within the acceptable range.*

CO2 emissions are negative and significant across all estimators: a one-tonne per-capita increase is associated with a 0.031-point ESI decline (system GMM). AR(1) rejects (p=0.012), as expected by construction; AR(2) does not reject (p=0.341); Hansen J does not reject instrument validity (p=0.268); and the instrument count (31) stays below the 40-country group limit. These diagnostics support system GMM as the preferred specification for dynamic bias and reverse causality, but establish robustness rather than definitive causal identification; the paper's language is calibrated accordingly.

Carbon Emissions and Biodiversity Loss: Interpretation

CO2 affects African biodiversity through several channels: rising temperatures alter

precipitation and species ranges and intensify drought in savannah and semi-arid zones (Niang et al., 2014), while ocean acidification and warming threaten coastal and freshwater biodiversity, including fisheries central to food security (Hoegh-Guldberg et al., 2007). As Section 4.6 shows, this is not an artefact of CO2 appearing in both the dependent and independent variable, since the same significant negative relationship holds against the CO2-free biodiversity sub-index.

Renewable Energy Consumption and Ecological Sustainability

Renewable energy is positive and significant across specifications: a one-point rise in renewable share is associated with a 0.0018-point ESI gain (system GMM), consistent with Section 2.4 (Alola et al., 2019; Apergis & Payne, 2010; Shahbaz et al., 2015) and with ecological modernisation theory. This is policy-relevant given Africa holds roughly 60% of the world's best solar resources (IEA, 2022) yet remains well below its renewable potential.

GDP and the EKC: Reconciling the U-Shaped ESI Result

The results support the EKC once the direction of variable coding is made explicit. Since ESI is coded so higher values mean greater sustainability, the negative GDP coefficient and positive squared term (Table 3) trace a U-shape in ESI itself, falling then rising with income. This is the same relationship as the conventional inverted-U EKC (Grossman & Krueger, 1995; Panayotou, 1993), expressed in terms of quality rather than degradation; degradation, coded oppositely, would rise then fall. The two are algebraically identical, so the finding is fully consistent with, not contrary to, the standard hypothesis. This paper uses the term 'EKC-consistent U-shaped ESI trajectory' throughout to avoid the ambiguity that follows from leaving variable coding implicit.

The estimated turning point, approximately USD 8,200 per capita, exceeds the income of nearly all sampled economies, so most remain on the degrading segment. This is consistent with Asongu et al. (2017), who find limited income-driven improvement in Sub-Saharan Africa, while comparable non-linearities appear in EU panels (Bekun et al., 2019), suggesting the curve's shape is not uniquely African. Absent intervention, continued growth is thus likely to intensify rather than ease ecological pressure over the medium term for most African economies.

Robustness Check: Biodiversity-Only Specification

Table 4 re-estimates system GMM using the CO2-free biodiversity sub-index (BIO) as the dependent variable, directly testing the concern in Section 3.2.1.

Table 4. Robustness: System GMM with BIO (CO2-Free) as Dependent Variable

Variable	System GMM (DV = BIO)
CO2 per capita	-0.019** (0.008)
Renewable energy share	0.0011** (0.0005)
GDP per capita (000s)	-0.033* (0.018)
GDP per capita squared	0.0019* (0.0011)
Population density	-0.0005** (0.0002)
Institutional quality	0.028 (0.021)
Lagged BIO (t-1)	0.387*** (0.076)
Observations (N)	812
Instrument count	31
AR(2) test (p)	0.298
Hansen J test (p)	0.241

Note: *BIO contains no CO2 information. SE in parentheses. ***p<0.01, **p<0.05, *p<0.10.*

CO2 remains negative and significant ($p<0.05$) even with a dependent variable purged of CO2 content, though smaller in magnitude than in the composite model (-0.019 vs -0.031), consistent with the variance decomposition in Section 4.2: part of the composite coefficient is definitional overlap, and a smaller but still significant part reflects a substantive ecological relationship. Conclusions on CO2 and biodiversity rely on this decomposed specification, not the composite ESI model alone.

Heterogeneity Across African Economic Typologies

Pooled continental estimates may mask heterogeneity across economic structures. The sample is split into four typologies: oil-producing (e.g., Nigeria, Angola, Algeria, Libya), industrialising (e.g., South Africa, Egypt, Morocco, Kenya), agrarian/low-income (e.g., Niger, Malawi, Burkina Faso, Ethiopia), and renewable-dependent economies (e.g., hydropower/geothermal-heavy Ethiopia, Kenya, Zambia, DRC). Table 5 reports sub-group system GMM coefficients.

Table 5. Heterogeneity Across African Economic Typologies

Typology	CO2 coef.	Renewable coef.	N (countries)
Oil-producing	-0.047*** (0.011)	0.0009 (0.0007)	6
Industrialising	-0.035*** (0.009)	0.0015** (0.0006)	9
Agrarian / low-income	-0.014* (0.008)	0.0022*** (0.0006)	15
Renewable-dependent	-0.011 (0.009)	0.0026*** (0.0007)	10

Note: *Separate system GMM per sub-sample, full covariates as in Table 3. SE in parentheses. ***p<0.01, **p<0.05, *p<0.10. Small sub-samples: read as directional, not precise, estimates.*

The emissions-sustainability trade-off is three to four times steeper in oil-producing and industrialising economies than in agrarian and renewable-dependent ones, and the renewable coefficient is statistically indistinguishable from zero in oil-producing economies — consistent with their more carbon-intensive, less renewable-developed energy systems. In agrarian and renewable-dependent economies the renewable coefficient is larger and more precisely estimated. A uniform continental policy prescription is therefore unlikely to be optimal.

Institutional Quality and Governance

Institutional quality is positively associated with sustainability, significant at 10% in the FE and system GMM models (Table 3), consistent with governance's broader role in African development outcomes (Asongu & Nwachukwu, 2016) extended here to the environmental domain, though the marginal effect is modest relative to CO2 and renewable energy.

Policy Implications

First, the robust CO2 effect, confirmed in both the composite and CO2-free specifications, underscores the urgency of mitigation: carbon pricing mechanisms (emissions trading, carbon taxes, REDD+) should be embedded in Nationally Determined Contributions (UNFCCC, 2015), with revenue channelled into renewables and biodiversity conservation. Second, investment priorities should differ by typology: further renewable scale-up for agrarian and renewable-dependent economies, and complementary carbon pricing plus industrial energy-efficiency regulation for oil-producing and industrialising ones, where renewable adoption alone appears insufficient (Section 4.7). Regional interconnection (e.g., Eastern and West African Power Pools) should be accelerated (IEA, 2022; IRENA, 2022). Third, since most African economies remain on the degrading segment of the EKC-consistent ESI trajectory (Section 4.5), biodiversity targets should be embedded in macroeconomic

planning, referencing the Kunming-Montreal Global Biodiversity Framework's 30x30 target (CBD, 2022). Fourth, governance reforms, stronger regulatory agencies, anti-corruption enforcement, and secure land tenure, should accompany the above, given institutional quality's moderating role. Fifth, biodiversity indicators should be integrated into national statistics through natural capital accounting frameworks such as the System of Environmental-Economic Accounting (United Nations et al., 2021).

Conclusion

This study examined carbon emissions, biodiversity decline, and sustainable development across African economies using FE, RE, and system GMM estimators, with full instrument, diagnostic, and regression-table reporting. Carbon-intensive growth is associated with lower sustainability, a relationship that survives a robustness check ruling out mechanical correlation with the composite dependent variable. Renewable energy mitigates this, more strongly in agrarian and renewable-dependent economies than in oil-producing and industrialising ones. Once variable coding is made explicit, the EKC evidence shows African economies are predominantly on the degrading segment of a trajectory fully consistent with the conventional inverted-U hypothesis, underscoring that income growth alone will not resolve ecological pressure at current income levels.

The study's contributions are fourfold: integrating biodiversity into a panel framework for Africa while transparently addressing the resulting mechanical correlation; applying system GMM with full instrument and diagnostic reporting while calibrating causal language to the design's limits; reconciling an apparently anomalous U-shaped ESI-GDP relationship with the conventional inverted-U EKC once variable coding is made explicit; and showing that pooled continental relationships mask material heterogeneity across economic typologies, cautioning against uniform policy prescriptions.

Limitations include constrained biodiversity-indicator availability, cross-country abstraction from within-country heterogeneity, and small typology sub-samples read as illustrative rather than precise. Future work should combine panel analysis with country case studies and spatial econometrics, and add trade openness, FDI, and technology transfer as further channels. African economies face a genuine reconciliation challenge between economic advancement and ecological integrity, one whose policy mix will differ across the continent's economic structures.

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