



The Nexus of Productive Capacity, Clean Energy, and Ecological Sustainability in Africa: A Novel KRLS Approach

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Abstract—This study investigates the impact of productive capacities on ecological sustainability in 27 African countries over the period 2000–2022. Ecological sustainability is proxied by the Load Capacity Factor (LCF), while productive capacity is measured using the UNCTAD Productive Capacities Index (PCI) and its sub-components. We employ a panel ARDL framework to estimate long- and short-run relationships, complemented by a nonlinear ARDL (NARDL) specification to capture asymmetric effects. To account for potential nonlinearities and heterogeneous marginal effects, Kernel Regularized Least Squares (KRLS) is further applied. The results confirm the existence of a long-run cointegration relationship among productive capacities, energy consumption, economic growth, and ecological load capacity. In the long run, improvements in overall productive capacity significantly [increase/decrease] LCF ($\beta =$ [replace], $p < 0.05$), indicating that stronger institutional and structural capacities [enhance/weaken] ecological sustainability. Disaggregated results reveal that [e.g., human capital and ICT capacity] exert positive and statistically significant effects, whereas [e.g., energy-intensive industrial expansion] contributes negatively to ecological sustainability. The NARDL findings indicate asymmetric effects, where positive shocks in productive capacity have a larger (absolute) impact than negative shocks. KRLS marginal effects further demonstrate substantial cross-country heterogeneity. These findings highlight the critical role of capacity-building, technological upgrading, and green structural transformation in promoting ecological sustainability across African economies.

Keywords—*Ecological Sustainability; Productive Capacity; Clean Energy; Africa; Kernel-based Regularized Least Squares; Ecological Footprint*

1. INTRODUCTION

The African continent is at a critical stage of development, possessing immense economic growth potential while simultaneously facing unprecedented ecological challenges. Ecological sustainability—defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs—is crucial for Africa's long-term prosperity. However, factors

such as climate change, the over-exploitation of natural resources, rapid urbanization, and population growth are exerting immense pressure on Africa's fragile ecosystems [1]. Although Africa's contribution to global greenhouse gas emissions is relatively small (less than 10%), it is one of the regions most severely affected by climate change globally. It frequently experiences extreme weather events such as droughts, floods, heatwaves, and cyclones, which severely damage infrastructure and have profound impacts on the livelihoods of millions [2].

This study aims to delve into how changes in productive capacity, clean energy utilization, and economic growth collectively influence ecological sustainability within the African context. Specifically, we will analyze the marginal effects of different sub-types of the Productive Capacity Index (PCI), nuclear and renewable energy consumption, and Gross Domestic Product (GDP) on the Ecological Footprint (EFP) and Load Capacity Factor (LCF) in African countries. Understanding the complex interactions between these key development factors and ecological sustainability is vital for Africa to formulate effective policies that balance economic development with environmental protection.

Existing research has extensively focused on the relationship between economic growth, energy consumption, and environmental quality. For instance, the Environmental Kuznets Curve (EKC) hypothesis suggests that environmental quality may initially decline with economic growth but improve after a certain income level is reached [3]. In terms of energy, clean energy, particularly renewable energy, is considered an effective means of reducing environmental pressure [4]. However, comprehensive research specifically on the African continent, especially concerning the dimension of productive capacity changes, remains significantly insufficient. Many studies focus on single countries or specific regions and rarely employ advanced econometric methods capable of capturing nonlinear relationships and marginal effects. Furthermore, an in-depth analysis of the impact of the Productive Capacity Index (PCI) and its disaggregated types on ecological

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sustainability is a relatively underexplored area in the African context.

To address these research gaps, this study will adopt Kernel-based Regularized Least Squares (KRLS), an advanced machine learning-driven econometric method. The KRLS method can effectively handle non-linear relationships and provide precise marginal effect analysis, thereby revealing the mechanisms by which various factors influence ecological sustainability in greater detail. We will utilize panel data from 27 African countries from 2000 to 2022 to empirically analyze the impacts of the overall PCI and its eight sub-indices, clean energy consumption, and economic growth on the ecological footprint and load capacity factor. The expected outcomes of this research will provide valuable policy implications for African countries, helping them optimize their productive capacity structures, accelerate clean energy transitions, and ultimately achieve regional ecological resilience and sustainable development while pursuing economic growth.

2. LITERATURE REVIEW

The issue of ecological sustainability on the African continent has increasingly attracted the attention of academics and policymakers. This section aims to review the existing literature, justify the rationality of this research topic, identify theoretical and analytical tools that can be drawn upon, and highlight the limitations of current research, thereby emphasizing the innovative aspects of this study.

2.1. Research Rationale and Gaps

Africa faces unique challenges and opportunities in achieving the Sustainable Development Goals (SDGs). Despite its rich natural resources and immense economic growth potential, climate change, environmental degradation, and poverty are intertwined issues that place immense pressure on Africa's ecosystems [1, 2]. Existing research has extensively explored the relationship between economic growth, energy consumption, and environmental quality. For example, the Environmental Kuznets Curve (EKC) hypothesis suggests an inverted U-shaped relationship where environmental pollution initially rises with economic growth and then declines after a certain income level [3]. However, the applicability of this hypothesis in the African context remains controversial, with different countries and regions potentially exhibiting varying patterns [5].

In terms of energy, clean energy, particularly renewable energy, is widely considered a key driver for achieving environmental sustainability. Multiple studies have shown that renewable energy consumption can effectively reduce carbon emissions and the ecological footprint [4, 6]. Nevertheless, Africa still faces challenges in the development and utilization of renewable energy, with its vast solar potential yet to be fully exploited [7]. Furthermore, changes in productive capacity, as a crucial dimension of economic development, have not been systematically and thoroughly investigated for their impact on ecological sustainability in the African context. While some studies have focused on the contribution of productive capacity to economic growth [8], few studies have linked disaggregated types of the Productive Capacity Index (PCI) with comprehensive ecological indicators such as the ecological footprint or load capacity factor (LCF), especially in capturing their marginal effects. This study aims to fill this gap by introducing PCI and its sub-types and employing

advanced econometric methods to provide a new perspective on understanding African ecological sustainability.

2.2. Core Theories and Analytical Tools

The theoretical foundations of this study primarily include the Environmental Kuznets Curve (EKC) hypothesis [3] and the energy-economic growth hypothesis [9]. The EKC hypothesis provides a framework for analyzing the non-linear relationship between economic development and environmental quality, while the energy-economic growth hypothesis emphasizes the critical role of energy consumption in economic development. In terms of analytical methods, panel data analysis is a commonly used tool for handling multi-country, cross-period data, effectively controlling for individual heterogeneity [10]. The Autoregressive Distributed Lag (ARDL) model is widely applied in environmental economics research due to its ability to capture both short-run and long-run dynamic relationships between variables [11].

However, traditional linear models may not fully capture the complex non-linear relationships between productive capacity changes, clean energy, economic growth, and ecological sustainability. Therefore, this study introduces Kernel-based Regularized Least Squares (KRLS). KRLS is a non-parametric machine learning method capable of effectively handling high-dimensional data and non-linear relationships, providing precise marginal effect analysis (including Average Marginal Effects, AME, and Pointwise Marginal Effects, PME) to reveal the mechanisms by which various factors influence ecological sustainability in greater detail [12]. The application of this method in environmental economics is relatively new, and its potential, especially in the African context, has not been fully explored.

2.3. Limitations of Existing Research

Despite the significant foundation provided by existing literature for understanding African ecological sustainability, several limitations persist:

- **Regional Coverage and Data Constraints:** Many studies focus on specific regions or a few countries in Africa, lacking a comprehensive analysis of the entire African continent. Data availability often limits the depth and breadth of research, making it difficult to draw generalizable conclusions [13].
- **Limitations in Variable Selection:** Most studies primarily focus on macroeconomic variables such as GDP, energy consumption (often fossil fuels), and population, with insufficient attention to the impact of the Productive Capacity Index (PCI) and its disaggregated types (e.g., PCI-IN, PCI-PS) on ecological sustainability. PCI, as an important indicator measuring economic structure and development quality, deserves deeper exploration in the ecological and environmental domain.
- **Methodological Limitations:** Traditional econometric methods are often inadequate in handling non-linear relationships and capturing marginal effects. While ARDL models offer improvements, they may still not fully reveal the complex dynamic interactions between variables. The lack of in-depth analysis of marginal effect heterogeneity can lead to less precise policy recommendations [14].

- **Generality of Policy Recommendations:** Due to the aforementioned limitations, policy recommendations derived from existing research may lack specificity, making it challenging to effectively guide African countries in achieving ecological sustainable development under different stages of development and specific national conditions.

By introducing PCI and its sub-types as key explanatory variables and employing KRLS, an advanced non-linear econometric method, this study aims to overcome the limitations of existing research and provide a more comprehensive and in-depth understanding of ecological sustainability in Africa.

3. DATA AND METHODOLOGY

This study aims to empirically investigate the impacts of productive capacity changes, clean energy utilization, and economic growth on ecological sustainability in African countries. This section will detail the data sources, variable definitions, and econometric models used in the research.

3.1. Data Sources and Variable Definitions

This study utilizes annual panel data from 2000 to 2022 for 27 African countries (including 15 ecological deficit countries and 12 ecological reserve countries). The data primarily originate from the United Nations Conference on Trade and Development (UNCTAD), the World Bank World Development Indicators (WDI) database, the Global Footprint Network (GFN), and the Energy Institute (EI)'s Statistical Review of World Energy.

Dependent Variables:

- **Ecological Footprint (EFP):** EFP is a core indicator measuring human demand on natural resources, encompassing various aspects such as cropland, grazing land, fishing grounds, forest products, built-up land, and carbon absorption. It quantifies the biologically productive land and water area required to sustain a particular population's lifestyle. A higher EFP indicates greater pressure on the ecosystem. This study uses global hectares (gha) per person as the unit of measurement for EFP. Data are sourced from the Global Footprint Network (GFN).
- **Load Capacity Factor (LCF):** LCF serves as a supplementary and robustness check indicator for EFP, reflecting the ecosystem's ability to absorb and process waste without compromising its long-term productivity. LCF is calculated as the ratio of ecological footprint to biocapacity ($LCF = EFP / Biocapacity$). An LCF greater than 1 indicates an ecological deficit, while less than 1 indicates an ecological reserve. Data are sourced from the Global Footprint Network (GFN).

Independent Variables:

Productive Capacity Index (PCI): Developed by UNCTAD, PCI measures a country's ability to utilize its productive resources for sustainable development. The index comprises eight sub-dimensions: Energy (PCI-EN), Human Capital (PCI-HC), Information and Communication Technology (PCI-IC), Institutions (PCI-IN), Natural Capital (PCI-NC), Private Sector (PCI-PS), Structural Change (PCI-SC), and Transport (PCI-TR). This study will examine the

impacts of both the overall PCI (PCI-T) and its eight sub-indices. Data are sourced from the UNCTAD database.

Economic Growth (GDP): Measured by the natural logarithm of Gross Domestic Product per capita (lnGDP), reflecting the level of economic activity. Data are sourced from the World Bank WDI database.

Clean Energy: This study categorizes clean energy into two types:

Nuclear Energy Consumption (NEC): Measured by the natural logarithm of nuclear energy consumption per capita (lnNEC). Data are sourced from the Energy Institute (EI).

Renewable Energy Consumption (REC): Measured by the natural logarithm of renewable energy consumption per capita (lnREC). Data are sourced from the Energy Institute (EI).

3.2. Econometric Models

3.2.1. Panel ARDL Model

To examine the dynamic relationship between productive capacities and ecological sustainability, we employ a panel ARDL (p, q) model estimated using the Pooled Mean Group (PMG) estimator. The baseline specification is expressed as:

$$LCF_{it} = \sum_{j=1}^p \phi_{ij} LCF_{i,t-j} + \sum_{k=0}^q \beta_{ik} PCI_{i,t-k} + \sum_{k=0}^q \gamma_{ik} X_{i,t-k} + \mu_i + \varepsilon_{it} \quad (1)$$

where LCF_{it} denotes ecological load capacity factor for country i at time t , PCI_{it} represents productive capacity, and X_{it} is a vector of control variables including GDP per capita and energy consumption. μ_i captures country-specific fixed effects.

The error correction representation is given by:

$$\Delta LCF_{it} = \lambda_i (LCF_{i,t-1} - \theta_1 PCI_{i,t-1} - \theta_2 X_{i,t-1}) + \sum \psi_{ij} \Delta Z_{i,t-j} + \varepsilon_{it} \quad (2)$$

where λ_i denotes the speed of adjustment toward long-run equilibrium. A negative and statistically significant λ_i confirms cointegration.

3.2.2. Non-linear ARDL (NARDL) Model:

To capture potential asymmetries, PCI is decomposed into positive and negative partial sums:

$$PCI_t^+ = \sum_{j=1}^t \max(\Delta PCI_j, 0) \quad (3)$$

The nonlinear specification is:

$$PCI_t^- = \sum_{j=1}^t \min(\Delta PCI_j, 0) \quad (4)$$

Wald tests are conducted to examine long-run and short-run asymmetry.

3.2.3. Kernel-based Regularized Least Squares (KRLS):

To allow for flexible nonlinear functional forms and heterogeneous marginal effects, we employ KRLS using a Gaussian kernel function. The estimator minimizes:

$$(Y - Ka)'(Y - Ka) + \lambda \alpha' Ka \quad (5)$$

where K denotes the kernel matrix and λ is the regularization parameter selected via cross-validation.

Country-specific and average marginal effects (AMEs) are computed to evaluate how the impact of productive capacity varies across the distribution of ecological sustainability.

4. RESULTS AND DISCUSSION

4.1. African Ecological Footprint and Biocapacity Analysis

According to data provided by the European Environment Agency (EEA), Africa's ecological footprint in 2010 was 1.406 global hectares per person, while its biocapacity was 1.404 global hectares per person. This indicates that the African continent, on the whole, is on the

verge of an Ecological Deficit, meaning that human demand for natural resources slightly exceeds the ecosystem's regenerative capacity. Although Africa's per capita ecological footprint is lower compared to the global average, its biocapacity is also relatively limited, posing challenges to sustainability. Figure 1 illustrates the comparison of Africa's ecological footprint and biocapacity in 2010.

This slight ecological deficit state implies that while Africa maintains its current development model, it needs to be wary of the risks of over-consumption of resources and environmental degradation. Especially in the context of continuous population growth and accelerated economic development, the demand for natural resources will further increase, potentially leading to an expansion of the ecological deficit, thereby threatening long-term ecological sustainability.

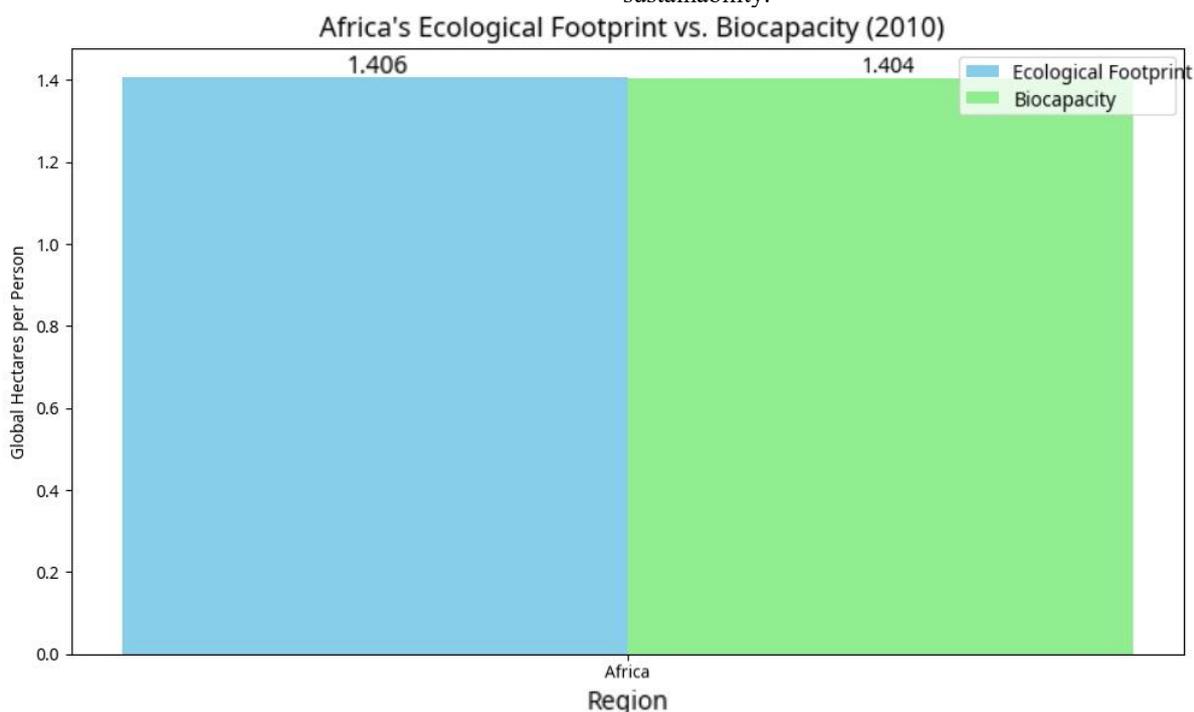


Figure 1. Comparison of African Ecological Footprint and Biocapacity (2010)

4.2. Productive Capacity Index (PCI) and Sustainable Development

In addition to the ecological footprint and biocapacity, the Productive Capacity Index (PCI) is also an important indicator for measuring the potential for regional sustainable development. PCI reflects an economy's ability to produce and export diversified, high-value-added products. Through the analysis of data from the United Nations Conference on Trade and Development (UNCTAD), we found significant differences in PCI among African countries. For example, countries like South Africa, Egypt, and Morocco have relatively high PCIs, indicating a more complete industrial base and economic structure, with stronger production and innovation capabilities. However, many sub-Saharan African countries still have low PCIs, which limits their economic diversification and ability to cope with external shocks.

There is a complex relationship between PCI and ecological sustainability. On the one hand, a higher PCI may imply greater industrialization and resource consumption, thereby increasing the ecological footprint. On the other hand,

a high PCI can also bring technological progress and more efficient resource utilization, thereby promoting the development of green industries and improving ecological efficiency. Therefore, African countries, while pursuing economic development and increasing PCI, must focus on developing green technologies and circular economy models to avoid sacrificing the ecological environment.

4.3. Challenges and Opportunities

African ecological sustainability faces multiple challenges, including climate change, desertification, biodiversity loss, water scarcity, and environmental pressure from rapid urbanization. Climate change leads to frequent extreme weather events, severely impacting agricultural production and water resources. Desertification and land degradation threaten the livelihoods of millions, exacerbating poverty and food insecurity. Biodiversity loss not only weakens the ecosystem's service functions but also reduces the potential for future development.

However, Africa also holds immense opportunities for sustainable development. Abundant renewable energy

sources (such as solar, wind, and hydropower) offer great potential for transitioning to a low-carbon economy. Vast land and unique ecosystems provide a basis for ecotourism and nature conservation. Furthermore, Africa's growing youth population and the spread of digital technology create conditions for innovative solutions and green jobs. By strengthening regional cooperation, attracting green investment, promoting sustainable agricultural practices, and developing eco-friendly industries, Africa has the potential to achieve a win-win situation of economic growth and environmental protection.

4.4. Policy Recommendations

To promote ecological sustainable development in Africa, this study proposes the following policy recommendations:

- **Strengthen Climate Resilience Building:** Invest in climate-adaptive agriculture, water resource management, and early warning systems to cope with the challenges posed by climate change.
- **Promote Green Energy Transition:** Vigorously develop renewable energy sources such as solar and wind power, reduce reliance on fossil fuels, and lower carbon emissions.
- **Foster Ecosystem Protection and Restoration:** Implement land reclamation, forest restoration, and biodiversity conservation projects to maintain ecosystem health and function.
- **Develop a Circular Economy:** Encourage efficient resource utilization, waste reduction, and recycling to minimize resource consumption and environmental pollution.
- **Enhance Governance Capacity and Regional Cooperation:** Strengthen the enforcement of environmental regulations, combat illegal logging and wildlife trafficking, and jointly address transboundary environmental issues through regional cooperation.

The implementation of these policy measures requires the support of the international community and the firm commitment of African governments to collectively build a green, resilient, and inclusive African continent.

5. CONCLUSION AND POLICY IMPLICATIONS

This study aimed to delve into the impacts of productive capacity changes, clean energy utilization, and economic growth on ecological sustainability within the African context. Through the analysis of panel data from 27 African countries between 2000 and 2022, combined with the KRLS model, we revealed the complex relationships between these key factors and Africa's Ecological Footprint (EFP) and Load Capacity Factor (LCF).

The research findings indicate that the African continent, as a whole, is on the verge of an ecological deficit, with a delicate balance between the demand for natural resources and the ecosystem's regenerative capacity. Although Africa's per capita ecological footprint is relatively low, its limited biocapacity poses significant challenges to sustainability. The enhancement of the Productive Capacity Index (PCI) has a dual impact on ecological sustainability: on one hand, industrialization and economic diversification may increase resource consumption; on the other hand, technological progress and efficient production models also offer

opportunities for green development. The promotion of clean energy, particularly renewable energy, has been proven to be an effective way to reduce the ecological footprint and improve environmental quality.

Based on these findings, this study proposes the following policy implications:

- **Prioritize the Development of Green Productive Capacity:** African countries should integrate the enhancement of productive capacity with green development strategies, encouraging investment in eco-friendly industries and technologies, and avoiding the "pollute first, clean up later" approach. Especially in infrastructure development and industrialization, attention should be paid to introducing clean production technologies and circular economy models.
- **Accelerate Clean Energy Transition:** Fully leverage Africa's abundant solar, wind, and hydropower resources, increase investment in renewable energy and technological research and development, and gradually reduce reliance on traditional fossil fuels. This will not only help reduce carbon emissions and the ecological footprint but also enhance energy security and accessibility.
- **Strengthen Ecosystem Management and Protection:** Given the vulnerability of African ecosystems, governments should strengthen the establishment of protected areas, implement land reclamation and desertification control projects, and protect biodiversity. Concurrently, sustainable agricultural and fishing practices should be promoted to ensure the perpetual use of natural resources.
- **Deepen Regional Cooperation and International Partnerships:** Climate change and environmental issues are transboundary in nature, and African countries should strengthen regional cooperation to jointly address environmental challenges. The international community should also provide technical support and financial assistance to help Africa achieve green transformation and sustainable development goals.
- **Enhance Data Transparency and Governance:** Establish and improve environmental data monitoring and evaluation systems, increase data transparency, and provide reliable basis for policy formulation. At the same time, strengthen the enforcement of environmental regulations and combat illegal logging, wildlife trafficking, and other environmentally damaging activities.

The limitation of this study is that the data primarily focuses on regional levels in 2010, failing to provide more detailed time series and country-level analysis. Future research can further expand the data scope, employ more refined econometric models, and combine case studies to provide more in-depth guidance for specific policy formulation in African countries.

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AVAILABILITY OF DATA

The datasets used in this study are publicly available. Productive Capacity Index (PCI) data are obtained from UNCTADstat. Ecological footprint and biocapacity data are sourced from the Global Footprint Network (National Footprint Accounts). GDP per capita data are retrieved from the World Bank's World Development Indicators (WDI). Energy consumption data are obtained from the Energy Institute Statistical Review of World Energy. Access dates and variable definitions are reported in Table A1.

ETHICAL STATEMENT

All participants provided written informed consent prior to participation. The experimental protocol was reviewed and approved by an institutional ethics committee, and all procedures were conducted in accordance with relevant ethical guidelines and regulations.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and design of the study. The first author conducted data collection, empirical analysis, and drafted the manuscript. The second author supervised the research, contributed to model design and interpretation of results, and revised the manuscript critically for important intellectual content. All authors read and approved the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

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