

Rethinking resource sustainability through economic complexity: A systemic environmental nexus study in Sub-Saharan Africa

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ABSTRACT

Resource depletion in Sub-Saharan Africa (SSA) poses a serious challenge to the region's development and its ability to achieve global sustainability objectives, particularly those outlined in the Sustainable Development Goals, such as Goal 12 on responsible consumption and production and Goal 15 on life on land. The region's heavy reliance on natural resources for economic growth and industrialization exacerbates the depletion of these resources, leading to environmental degradation, and heightened socio-economic vulnerabilities. In response to this, economic complexity presents a potential strategy to reduce dependence on resource-intensive sectors and promote sustainable growth. This study explores this strategy, investigating the effect of economic complexity on resource depletion, specifically focusing on energy, forest, and mineral depletion in 33 SSA countries from 1998 to 2022. Employing a variety of methods, including the fixed-effects Driscoll and Kraay estimator, two-step system GMM, IV-GMM, and quantile regression, the results provide strong evidence that greater economic complexity reduces resource depletion, primarily through technological advancement and diversification. The results, robust to a battery of checks, also identify the internet and income as potential transmission channels through which economic complexity may act on resource depletion in the region. Based on these findings, the study recommends policies that foster technological innovation, industrial diversification, and sustainable resource management, alongside financial support for green initiatives, to curb resource depletion while promoting economic resilience.

1. Introduction

Sub-Saharan Africa (SSA) is home to some of the world's most resource-rich countries, yet its natural resources are being rapidly depleted, with significant consequences for both the environment and economic development [1]. The depletion of energy, forest, and mineral resources in the region is linked to unsustainable extraction practices, weak governance frameworks, and a growing dependence on resource exports [2,3]. This trend exacerbates environmental degradation, heightens social inequalities, and constrains long-term economic growth [4]. While traditional policy responses, such as conservation efforts and resource management strategies, have sought to address these issues, they have often been limited in scope and impact [5,6]. Consequently, alternative approaches that go beyond conventional resource governance are needed to tackle the underlying causes of depletion.

One such approach that has gained increasing attention is the concept of economic complexity [7–10]. Economic complexity refers to the diversity and sophistication of a country's productive capabilities, with more complex economies tending to generate higher-value

products and demonstrate greater resilience to external shocks [11,12]. This concept is particularly relevant for resource-dependent regions like SSA, where economic diversification has historically been slow and heavily reliant on resource extraction. The combination of natural resource depletion and economic complexity offers a distinct opportunity to examine how progress in economic diversification and sophistication can address the challenges brought about by resource depletion in SSA economies. By reducing dependence on extractive industries, SSA economies can encourage more sustainable and resilient growth, breaking through conventional development obstacles and supporting a more inclusive economic environment.

This study conceptualizes the “economic complexity–resource depletion nexus” as the dynamic and mutually reinforcing relationship between a country's productive knowledge base and the rate at which natural resources are extracted or degraded. In theory, higher economic complexity can mitigate resource depletion by enabling a structural shift away from raw commodity dependence toward value-added, innovation-driven sectors that are less intensive in land, energy, and material inputs. However, the relationship is not unidirectional; increasing

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complexity can also intensify resource depletion when diversification occurs within resource-processing or mineral-based manufacturing chains, thereby scaling extraction and environmental pressure. Likewise, resource depletion itself feeds back into complexity, where rapid depletion may erode the institutional stability and investment capacity needed for upgrading, while well-governed resource rents can alternatively fund skill development, infrastructure, and technological learning that facilitate diversification. The nexus thus reflects a two-way causal system governed by feedback loops, path dependence, and policy choices. Precisely because African economies simultaneously face the imperative to industrialize and the risk of deepening resource dependence, clarifying how complexity interacts with natural resource use is central to understanding their sustainable development trajectory.

Natural resource depletion and economic complexity are important factors shaping the future of SSA's economies [13]. Natural resource depletion in SSA is occurring at significantly higher rates compared to the global average, with the region's total natural resource depletion estimated at 8.5 % of GDP, compared to the global average of 5.1 % [14]. This trend is evident across energy, forests, and minerals, with energy depletion in SSA reaching 2.3 % of GDP, more than double the global average of 1.2 % [15]. SSA's reliance on fossil fuels, particularly oil and gas in countries like Nigeria and Angola, is leading to extraction rates that surpass reserves replacement, intensifying depletion concerns. In the forestry sector, SSA loses approximately 0.7 % of its forests annually, a deforestation rate significantly higher than the global average of 0.18 % [16,17]. Deforestation, driven by agriculture, logging, and urbanization, is especially prominent in countries such as Cameroon, the Democratic Republic of Congo, and Ghana, undermining biodiversity and local livelihoods. In terms of mineral depletion, SSA is extracting metals like gold, copper, and cobalt at an accelerating pace, with the mineral depletion rate in the region estimated at 1.5 % of GDP, compared to the global average of 0.8 % [18]. This heightened extraction is prevalent in countries like South Africa and Zambia, where mining activities often lack sustainable practices and reinvestment, further depleting non-renewable resources.

Economic complexity in SSA has shown gradual improvement in recent years, with some countries making notable strides [19]. For instance, South Africa has advanced its economic complexity by developing sectors such as automotive manufacturing and pharmaceuticals [20]. However, despite these pockets of progress, the overall performance of SSA countries on the Economic Complexity Index (ECI) remains low. Stylized facts highlight the stark reality of SSA's performance on the global ECI. According to the 2022 rankings by the Observatory of Economic Complexity,¹ only South Africa (ranked 59th globally) demonstrates moderate economic complexity, driven by sectors like automotive manufacturing and electronics. In contrast, most African nations remain at the lower end of the spectrum, with countries such as Nigeria (ECI rank: 132nd) and Angola (ECI rank: 126th) heavily reliant on crude oil exports. Across SSA, the average ECI score is among the lowest globally, reflecting limited industrial diversification and heavy dependence on primary commodities [21]. For instance, more than 70 % of Sub-Saharan Africa's exports consist of unprocessed raw materials, a striking contrast to East Asia, where trade is primarily driven by high-value manufactured goods [22]. The following visualization illustrates the ECI and the Economic Complexity Ranking of each country in the World, where SSA is seen as the region depicting the lowest ECI, as shown in Fig. 1.

Recent research suggests that countries with higher economic complexity are better equipped to transition from resource-based to more sustainable, diversified economies [1,23–26]. However, while economic complexity has been studied in relation to resource exhaustion, its specific impact on different types of natural resource depletion remains underexplored, particularly in the context of SSA. The depletion

of natural resources in SSA continues to present a challenge, and traditional policy measures have struggled to produce lasting change. This study seeks to bridge the gap in the literature by exploring the relationship between economic complexity and natural resource depletion, specifically, energy depletion, forest depletion, and mineral depletion. By examining how product diversification and sophistication relate to resource use and sustainability, this research aims to contribute new insights into whether economic complexity can serve as a driver for more sustainable resource management in the region. The central question guiding this study is: Can increasing economic complexity help reverse the trend of natural resource depletion in SSA? This question is motivated by the hypothesis that higher levels of economic complexity are associated with more efficient resource utilization, increased value addition, and a shift from extractive to knowledge-intensive industries [1,23].

This study makes several contributions to the literature on economic complexity and natural resource management, particularly in the context of SSA. Building on and expanding the studies of Kelly et al. [1], the present one provides new insights into a region that has long remained underexplored despite being one of the most resource-dependent in the world. Unlike previous studies that have primarily focused on global or cross-regional analyses, this study situates the analysis within SSA, where natural resources account for a substantial share of government revenue, exports, and livelihoods. Examining SSA is especially important because the region faces the dual challenge of harnessing resource rents for growth while mitigating the adverse ecological and economic consequences of resource depletion. The study not only examines the direct link between economic complexity and natural resource depletion but also extends the literature by empirically assessing the indirect pathways through which economic complexity may influence depletion outcomes. Furthermore, the disaggregation of natural resource depletion into energy, mineral, and forest categories allows for a more granular understanding of how complexity affects different resource domains, which is important given their heterogeneous roles in SSA's economies and ecosystems.

Methodologically, the study strengthens causal inference by employing both Driscoll and Kraay estimators, which address cross-sectional dependence, and instrumental variable generalized method of moments (IV-GMM) techniques, which mitigate potential endogeneity concerns. This empirical strategy ensures that the results are robust and reliable. The findings suggest that higher levels of economic complexity in SSA are associated with reduced depletion of natural resources, underscoring the role of productive diversification and knowledge intensity in fostering sustainability. In doing so, the study contributes to the literature on the sustainability implications of economic complexity and offers evidence relevant to the broader discourse on structural transformation in resource-dependent economies. At the same time, it informs ongoing efforts to achieve the SDGs, particularly SDG 12 on responsible consumption and production and SDG 15 on life on land, in the context of growing concerns about environmental degradation and economic vulnerability in SSA.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature, Section 3 describes the methodology employed, Section 4 presents the findings, discusses the results, and includes robustness checks, and Section 5 concludes the study.

2. Literature review

2.1. Theoretical underpinnings

This study is grounded in the Resource Curse Hypothesis (Paradox of Plenty) and the Environmental Kuznets Curve (EKC) Hypothesis, both of which provide a theoretical framework for understanding how economic complexity can influence the trajectory of natural resource depletion. Looking at the Resource Curse Hypothesis, also known as the Paradox of Plenty, it emerged as a counterintuitive economic theory suggesting that

¹ <https://oec.world/en/profile/bilateral-country/tun/partner/zaf>.

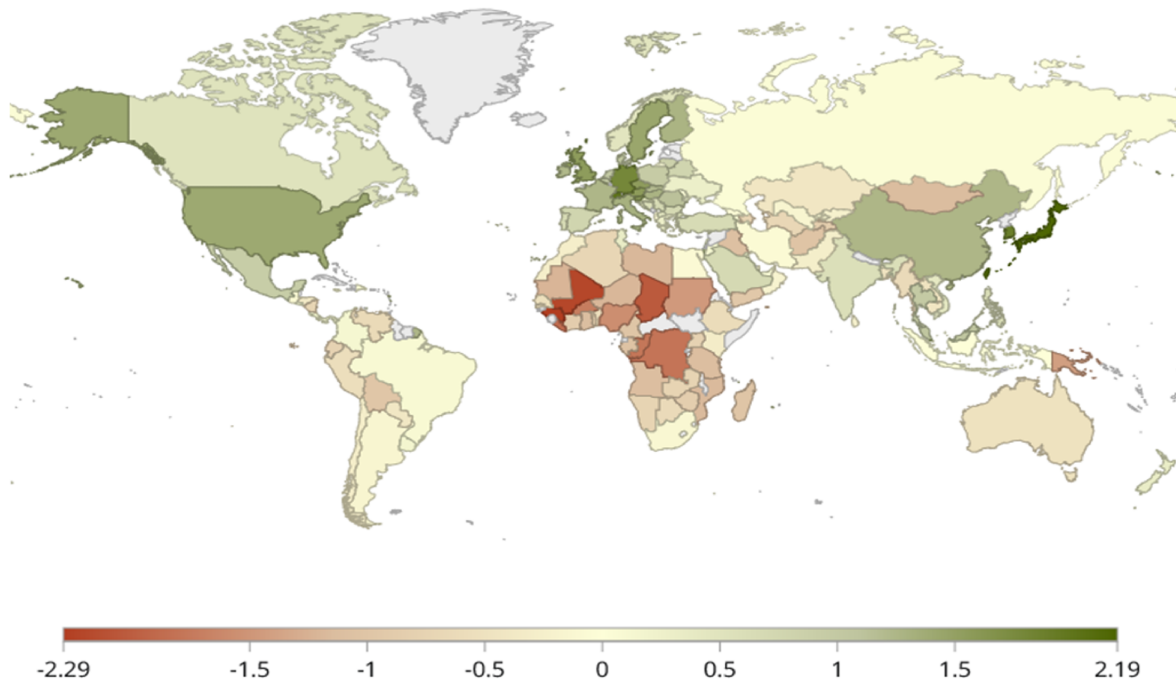


Fig. 1. 2022 Economic complexity Index by country. Source: OEC.

countries rich in natural resources tend to experience slower economic growth, weak industrial development, and poor governance outcomes compared to resource-scarce nations [27,28]. The origins of this hypothesis can be traced back to early observations by Sachs and Warner [29], who empirically demonstrated that resource-abundant economies often perform worse in terms of GDP growth than their resource-poor counterparts. The fundamental explanation lies in the overreliance on natural resource exports, which leads to economic distortions such as Dutch Disease—a phenomenon where resource booms appreciate the real exchange rate, making manufacturing and other tradable sectors less competitive [30]. Additionally, resource wealth often weakens institutional development, fostering rent-seeking behavior, corruption, and policy mismanagement [31]. Over time, scholars expanded the theory to incorporate broader political and social dimensions, arguing that resource abundance tends to entrench authoritarianism and hinder economic diversification, as governments finance their expenditures through resource rents rather than through taxation, thereby reducing incentives for accountability and institutional reforms [32]. This theoretical framework provides a lens for understanding the challenges faced by resource-rich economies, particularly in regions like SSA, where dependence on extractive industries has stifled industrialization and innovation-driven growth.

Economic complexity offers a pathway to counteract the resource curse by promoting product diversification, value addition, and knowledge-intensive industries—key mechanisms that can mitigate resource depletion. The ECI suggests that countries capable of producing and exporting sophisticated goods tend to achieve sustained economic growth and are less susceptible to resource dependency. In the context of SSA, where many economies rely heavily on the export of raw materials, increasing economic complexity can shift production structures toward high-value industries, reducing pressure on natural resource extraction [23]. Moreover, economic complexity fosters technological advancement and institutional improvements, which can enhance resource efficiency and promote sustainable management practices [24]. The non-linear relationship between economic complexity and resource depletion suggests that, in the early stages of industrialization, increasing complexity may initially lead to higher resource consumption due to rising production demands, but beyond a certain threshold,

enhanced technological capabilities and innovation drive a transition toward more sustainable economic activities [25]. This aligns with the works of Kelly et al. [1], who argue that diversifying production structures in resource-rich economies helps to decouple economic growth from resource exploitation, thus reversing the trend of depletion.

The Environmental Kuznets Curve Hypothesis which originated from the broader Kuznets Curve proposed by Kuznets [33], suggests an inverted-U relationship between economic development and income inequality. This concept was later extended to environmental economics by Grossman and Krueger [34], who hypothesized that environmental degradation initially increases with economic growth but declines after reaching a certain level of income. The logic behind the EKC is that in the early stages of industrialization, economies prioritize rapid economic expansion over environmental sustainability, leading to higher pollution, deforestation, and resource depletion [35]. However, as income rises, structural shifts toward knowledge-based industries, increased public demand for environmental quality, and stronger regulatory frameworks lead to a decline in environmental degradation. This transition is supported by technological advancements that improve energy efficiency and resource management, as well as by institutional reforms that enhance governance and enforcement of environmental regulations [36]. Despite its theoretical appeal, the EKC has been widely debated, with some studies arguing that the relationship between economic growth and environmental quality is more complex and depends on factors such as governance, trade openness, and sectoral composition [37].

Applying the EKC to the relationship between economic complexity and resource depletion provides valuable insights into how industrial sophistication can influence sustainable development. In the early stages of industrial development, increasing economic complexity may lead to greater resource exploitation, as economies shift from agrarian structures to manufacturing and extractive industries that demand more raw materials [23]. However, once a country reaches a certain threshold of complexity, technological innovation, efficiency gains, and structural transformation drive a reduction in resource depletion. More complex economies tend to invest in sustainable practices, such as circular economies, renewable energy, and environmentally friendly production processes, which help mitigate resource depletion [38]. Thus,

integrating economic complexity into the EKC framework highlights how higher levels of productive sophistication can serve as a mechanism for reversing resource depletion, offering policy insights for resource-dependent regions like SSA.

2.2. Economic complexity and resource depletion: possible transmission channels

2.2.1. The internet channel

The Internet is used in this study as a potential intermediate channel for two main reasons: first, it serves as a powerful reflection of innovation by enabling information accessibility, which in turn fuels advancements in several fields. Second, it reveals the institution's transparency. Therefore, it could indirectly absorb the institutional development. As nations enhance their economic complexity, particularly through the growth of high-tech industries and the digital economy, they foster greater access to and demand for internet services [39]. Economic complexity facilitates innovation, creating conditions that support the expansion of internet infrastructure, broadband connectivity, and digital services [20,40]. This advancement in internet capabilities, in turn, enables more efficient processes, promotes digital entrepreneurship, and encourages knowledge exchange, thus supporting further economic growth and technological development [41].

Through its ability to enhance information sharing and facilitate the development of new industries, the internet has the potential to both mitigate and exacerbate natural resource depletion. On the one hand, it enables more efficient use of resources by fostering innovation in sustainable technologies, such as renewable energy or resource-efficient practices [42] including artificial intelligence features and technologies. On the other hand, it can amplify consumption patterns by enabling the rapid spread of products and services that demand high resource use, such as e-commerce and cloud computing [43]. As such, the internet can influence how economic complexity interacts with resource depletion, depending on how it is harnessed for both technological progress and consumption behaviors [44].

2.2.2. Income channel

An increase in economic complexity is generally associated with higher income levels due to the increased productivity and higher value-added goods being produced [7]. The diversification of industries and the shift towards more sophisticated products enable economies to create better-paying jobs, promote innovation, and attract investments. Consequently, a more complex economy tends to generate higher income per capita, which may enhance the overall economic well-being of a country [39]. Higher income levels, driven by economic complexity, have implications for resource use, as more affluent populations typically exhibit greater consumption of goods and services, thereby escalating the demand for natural resources.

Income, as a transmission channel in the economic complexity-resource depletion nexus, may significantly impact the rate of natural resource depletion. The relationship between income and resource depletion is often characterized by the EKC, which posits that as income rises, resource extraction and environmental degradation initially increase but may decline once a certain income threshold is reached [45, 46]. In the context of more complex economies, the increase in income often leads to higher consumption of energy, minerals, and other resources [29]. However, economic complexity might also lead to more sustainable practices as industries evolve towards higher technological sophistication, which can reduce resource intensity [47].

Fig. 2 visually depicts the conceptual framework of this study, illustrating the pathways through which economic complexity may influence the depletion of natural resources.

2.3. Empirical literature

A growing body of literature has examined the role of economic

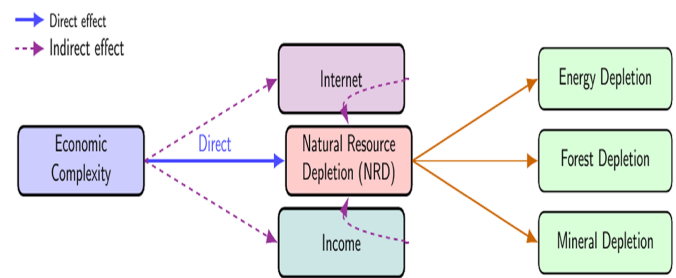


Fig. 2. Conceptual framework of the economic complexity-resource depletion nexus.

Source: Author's construction

complexity in relation to natural resources, with significant insights emerging from recent empirical work. For example, Kelly et al. [1] provide compelling evidence on the inverse relationship between economic complexity and resource depletion, revealing that higher economic complexity significantly reduces natural resource depletion across 36 Sub-Saharan African countries from 1997 to 2017. Their findings, which are robust across various estimation techniques and models, suggest that government expenditure on education and GDP per capita play crucial roles in curbing resource depletion. However, urbanization, foreign direct investment, and energy consumption accelerate resource exhaustion. This highlights the need for policies aimed at fostering economic diversification and strengthening sustainable resource management practices in the region. In a similar vein, Ajide [48] investigates the causal relationship between the natural resource curse and economic complexity in 32 African economies, finding that reliance on natural resources negatively impacts economic complexity. The study also emphasizes the importance of financial development and infrastructure, including telephone subscriptions, in enhancing economic sophistication, further supporting the argument that economic complexity can reduce the negative effects of resource dependence. Additionally, Mesagan and Vo [49] explore the mediating role of economic complexity in the resource-growth nexus in 28 African countries, uncovering that while resource wealth has a positive but insignificant effect on growth in both the short and long term, economic complexity significantly promotes growth in the long term, thereby demonstrating its potential for fostering sustainable economic growth from resource endowments.

Beyond its direct relationship with resource depletion, economic complexity has also been linked to shifts in resource rent dynamics. Ul-Durar et al. [24] delve into the relationship between economic complexity and resource rents in 20 resource-rich economies, uncovering a curvilinear relationship where economic complexity increases forest, coal, and mineral rents at low extraction levels but diminishes overall resource rents at higher extraction levels. This inverse U-shape relationship suggests that as economies become more complex, they shift from traditional resource extraction towards more sophisticated and sustainable practices, supporting the global push for clean energy transitions. A similar pattern emerges from the work of Canh et al. [23], which explores 90 economies from 2002 to 2017, noting that economic complexity modestly impacts total resource rents, with significant effects in low-income and high-income economies, but not in upper-middle-income ones. These findings emphasize the importance of economic complexity in shifting away from unsustainable reliance on mineral and fossil fuel rents, offering a path toward more diversified and sustainable economies. Furthermore, Ahmad et al. [50] emphasize that while resource rents can hinder sustainable development, both economic complexity and environmental regulations play an important role in fostering sustainability. The study's findings suggest that regulatory frameworks, when combined with increased economic sophistication, can effectively counterbalance the detrimental effects of resource rents, supporting the broader agenda of sustainable development.

Recent empirical studies across diverse contexts demonstrate that economic complexity serves as a driver of environmental sustainability, though its relationship with institutional and sectoral factors varies by region. Lee et al. [51] establish this foundational relationship in OECD countries, showing how knowledge-intensive production structures improve environmental performance through advanced technological capabilities. This finding is reinforced by Lin et al.'s [52] analysis of Chinese cities, where economic complexity boosts green growth via innovation and industrial upgrading, particularly when supported by government policies and public engagement. The European context examined by Saud et al. [53] introduces important nuances: while confirming economic complexity's positive role in sustainable development across EU states, their N-shaped EKC analysis reveals divergent effects of complementary factors - natural resources hinder sustainability whereas renewable energy and stock markets show regionally heterogeneous impacts.

2.4. Literature gap

Despite the growing body of literature on the relationship between economic complexity and natural resource management, several gaps remain that the present study seeks to address. Firstly, while existing research predominantly focuses on broad measures of resource depletion or rents, there is limited attention to the decomposition of resource depletion into specific categories such as energy, forest, and mineral depletion. This study contributes by offering a detailed disaggregation of resource depletion, which has not yet been explored in the literature. Moreover, while Kelly et al. [1] and others have identified an inverse relationship between economic complexity and resource depletion, the non-linear effects of economic complexity on resource depletion remain underexplored. This study addresses this gap by investigating potential non-linear relationships, which could reveal more insights into how economic complexity impacts resource use at different stages of economic development. Furthermore, while studies have explored the direct effects of economic complexity on resource management, few have proposed or tested the potential transmission channels through which economic complexity could influence resource depletion. This study fills this gap by proposing and testing possible transmission channels, offering a more comprehensive understanding of the mechanisms at play. Lastly, the focus of most existing research on African economies has been either on limited country samples or has failed to disaggregate regions based on their unique challenges and characteristics. This study specifically focuses on SSA, a region with diverse economies that face both high resource dependence and pressing sustainability challenges, providing insights into how economic complexity can mitigate the region's natural resource depletion.

3. Methodology

3.1. Data and source

This study relies on secondary data obtained from the Observatory of Economic Complexity (OEC)² and the World Development Indicators (WDI). The dataset covers 33 SSA countries³ over the years 1998–2022, with the timeframe chosen based solely on data availability. It is important to note that the panel is unbalanced because some variables are unavailable for certain countries and periods. To minimize bias, we addressed this missingness through deletion, ensuring that the retained

sample remains consistent with the study's objectives. SSA is chosen as the study region due to its high dependence on resource extraction, low levels of economic diversification, and vulnerability to environmental degradation [10]. The region's economies are predominantly resource-driven, with exports heavily concentrated in raw materials such as oil, minerals, and timber, making them highly susceptible to depletion and price volatility. Despite its vast natural wealth, SSA struggles with weak industrialization, limited technological advancement, and slow progress in moving up the value chain, all of which hinder sustainable economic growth [54]. Given that economic complexity emphasizes diversification and the sophistication of productive capabilities, understanding its role in mitigating resource depletion in SSA is important for shaping policies that foster sustainable development, reduce reliance on extractive industries, and promote long-term economic resilience. Preliminary findings, as depicted in Fig. 3, indicate a negative association between economic complexity and various resource depletion variables, including total natural resource depletion. This relationship is examined in greater detail in the later sections of the study. The descriptive statistics for the data used are presented in Table 1, while Table 2 displays the relationships between Resource depletion, economic complexity, and the control variables.

3.2. Definition of variables

3.2.1. Dependent variable

As dependent variable, the present study employs a vector of variables (Energy, Forest, Mineral, and total natural resource depletion) all representing resource depletion and given their documented impacts on economic growth and environmental sustainability [55,56]. According to the World Development Indicators (WDI) database, *Energy depletion* (% of GNI) is the ratio of the value of the stock of energy resources to the remaining reserve lifetime. It covers coal, crude oil, and natural gas. *Mineral depletion* (% of GNI) is the ratio of the value of the stock of mineral resources to the remaining reserve lifetime. It covers tin, gold, lead, zinc, iron, copper, nickel, silver, bauxite, and phosphate. *Net forest depletion* (% of GNI) is calculated as the product of unit resource rents and the excess of round wood harvest over natural growth. *Total Natural Resource Depletion* (TNRD) (% of GNI) is the sum of net forest depletion, energy depletion, and mineral depletion. All these variables are obtained from the WDI repository.

3.2.2. Independent variable

The independent variable in our study is Economic Complexity, measured using the ECI and obtained from the Observatory of Economic Complexity repository. The ECI captures the diversity and sophistication of goods and services that a country is capable of efficiently producing [11]. Unlike traditional economic indicators, the ECI delves into the structural characteristics of an economy, offering insights into its productive capabilities and underlying knowledge base. This measure is instrumental in assessing a nation's potential for sustainable economic growth, innovation, and resilience in the face of global economic changes. The ECI has been widely utilized in empirical research to analyze various economic phenomena, particularly in the context of development and structural transformation. For example, studies by Doğan et al. [57], Nguéda and Kelly [58], Kamguia et al. [59], and Ketu et al. [60] have effectively employed the index to explore the relationship between economic complexity and outcomes such as economic growth, foreign aid, and informality. Alternatively to this variable, we employ the technology ECI developed by Stojkoski et al. [61]. The Technological ECI is computed using data from the World Intellectual Property Organization's International Patent System.

In addition to the independent variable and following the determinants of resource depletion, we introduce control variables into the model. These are Urbanization measured as a % of urban population [62,63], Industrialization, captured using Manufacturing value added in % of GDP [64], Trade as a % of GDP [65,66], Financial development

² <https://oec.world/en/explorer>.

³ Angola, Benin, Botswana, Burkina Faso, Cameroon, Chad, Congo, Dem. Rep, Congo, Rep, Côte d'Ivoire, Ethiopia, Gabon, Ghana, Guinea, Kenya, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, Zimbabwe.

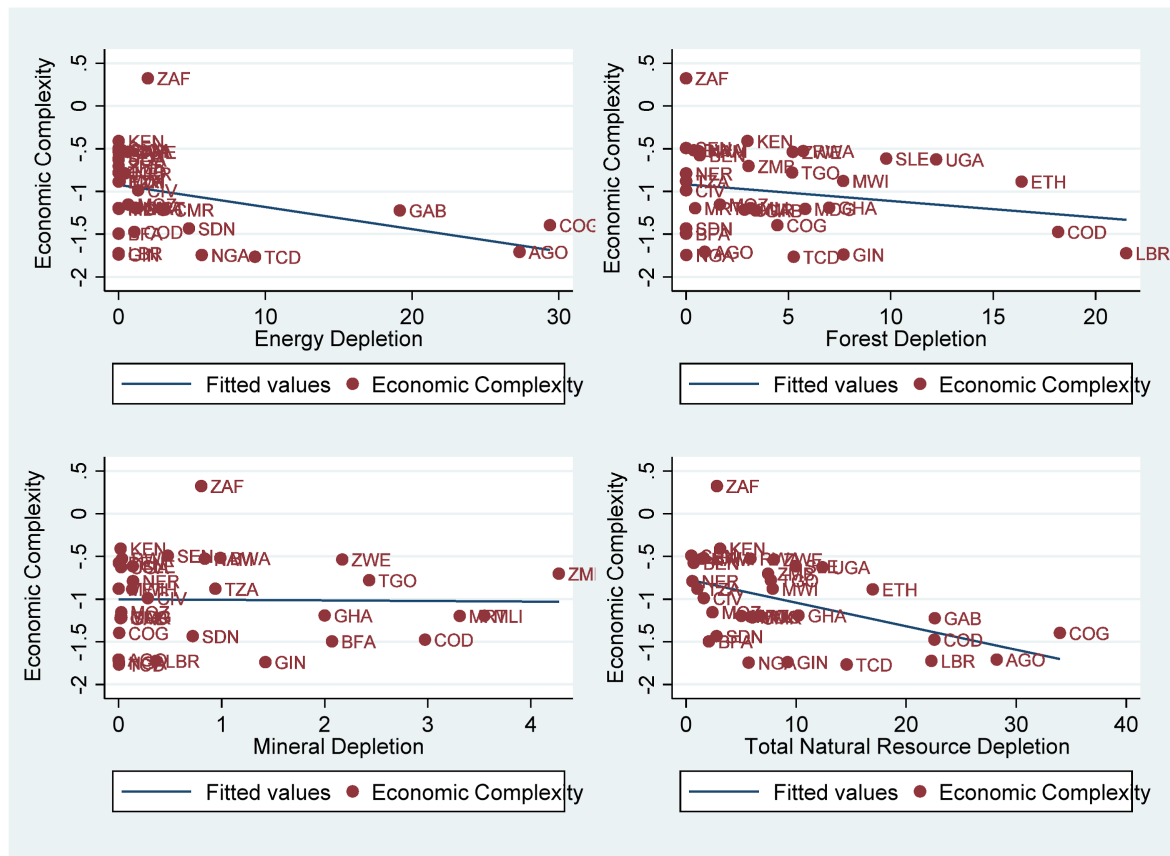


Fig. 3. Economic complexity versus Resource Depletion.

Source: Author's Construction

Table 1
Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
Energy Depletion	793	3.259	8.191	0	59.929
Forest Depletion	820	4.632	6.122	0	42.955
Mineral Depletion	792	0.917	2.007	0	22.66
TNRD	778	8.842	9.656	0	65.208
ECI	825	-1.008	0.54	-2.778	0.519
Urbanization	825	39.135	16.215	13.244	90.735
Industrialization	825	26.147	12.005	1.041	72.717
Trade	733	62.879	24.926	2.699	156.862
Financial dev	775	25.053	14.348	0.023	151.549
Military exp	759	1.659	1.277	0.22	17.335
Inflation	825	16.06	99.981	-27.049	2630.123

Note: Inflation is used without a logarithmic transformation because some observations included negative values.

Source: *Author's Construction*. Obs. and Std.Dev. respectively refer to the number of observations, and the standard deviation.

captured using Domestic credit to private sector in % of GDP [67,68], Military expenditure in % of GDP [69], and Inflation [70]. All these variables are derived from the WDI dataset.

3.3. Model and estimation strategy

Drawing inspiration from the works of Kelly et al. [1], we empirically specify the following model in baseline:

$$Depletion_{it} = \alpha + \beta ECI_{it} + \varphi X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

Where $Depletion_{it}$ represents the vector of resource depletion variables, comprising energy depletion, forest depletion, mineral depletion and

total natural resource depletion for country i during period t ; ECL_{it} refers to the economic complexity index; δ_t denotes a time-fixed effect that captures shocks influencing resource depletion across multiple countries simultaneously; μ_i represents country-specific factors; ε_{it} is the error term, assumed to be normally distributed; α , β , and φ are the parameters to be estimated; and X is a vector of control variables, including urbanization, industrialization, trade openness, financial development, military expenditure, and inflation.

Before choosing the regression technique, it is important to evaluate the presence of cross-sectional dependence, which has become more common in panel data due to the increasing globalization between countries. As indicated in Table A1 of the Appendix, all of our series show evidence of cross-sectional dependence. To tackle this, we apply Pesaran's second-generation unit root test as apparent in Table 3. Second-generation tests are beneficial because they account for cross-sectional dependence, unlike first-generation panel unit root tests, which assume cross-sectional independence [71].

As shown in Table 3, since all variables are stationary at their levels, and to enhance the robustness of statistical inference and ensure reliable standard errors in the panel analysis, multiple estimation techniques are utilized. These include the Driscoll and Kraay fixed effects method, the Instrumental Variable Generalized Method of Moments (IV-GMM), the two-step System GMM estimator, and quantile regression. To estimate Equation (1), the fixed effects of Driscoll & Kraay's [72] standard error correction is used to manage potential cross-sectional dependence across the panels (Kelly & Nembot Ndeffo, 2024). According to Hoechle [73], Driscoll and Kraay standard errors also correct for heteroscedasticity by utilizing a weighted average of both the between-group and within-group variances to compute the variance-covariance matrix of the model parameters.

To address concerns of endogeneity, we use both the two-step system

Table 2
Matrix of correlations.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) Energy Depletion	1.000										
(2) Forest Depletion	0.058	1.000									
(3) Mineral Depletion	0.164	0.013	1.000								
(4) TNRD	0.833	0.460	0.064	1.000							
(5) ECI	−0.389	−0.180	−0.055	−0.454	1.000						
(6) Urbanization	0.466	0.205	0.047	0.323	0.039	1.000					
(7) Industrialization	0.762	0.038	0.098	0.687	0.333	0.581	1.000				
(8) Trade	0.483	0.060	0.134	0.433	0.229	0.485	0.593	1.000			
(9) Financial dev	−0.116	−0.381	−0.088	−0.281	0.433	0.328	0.011	0.236	1.000		
(10) Military exp	−0.279	−0.108	−0.015	−0.199	0.103	0.096	0.360	0.331	0.232	1.000	
(11) Inflation	0.001	0.032	0.002	0.017	−0.061	−0.013	−0.018	−0.060	−0.085	−0.082	1.000

Source: *Author's Construction*

Table 3
The Pesaran's panel unit root test in the presence of cross section dependence.

Variables	Test at level		Level of Integration
	Z[t-bar]	P-value	
Energy Depletion	−4.282	0.000	I(0)
Forest Depletion	−8.071	0.000	I(0)
Mineral Depletion	−3.766	0.000	I(0)
TNRD	−5.809	0.000	I(0)
ECI	−3.646	0.000	I(0)
Urbanization	−13.923	0.000	I(0)
Industrialization	−2.674	0.003	I(0)
Trade	−1.669	0.047	I(0)
Financial dev	−0.261	0.000	I(0)

Source: *Author's Construction*

GMM and IV-GMM estimation methods. The system GMM, originally developed by Arellano and Bond [74], is particularly useful for addressing endogeneity in dynamic panel models. However, a key issue with system GMM is the potential for instrument proliferation, which can compromise the validity of Hansen's test, as highlighted by Kelly [75]. To counter this, we carefully selected instruments, collapsing them according to Roodman's [76] method to ensure that the number of instruments remained smaller than the number of cross-sections, following the approach of Kelly and Radler [77]. Specifically, the first lag of the explanatory variables was used as instruments, in line with established recommendations for valid instruments [7].

The IV-GMM approach was also chosen for its effectiveness in addressing cross-sectional dependence and heteroscedasticity issues in our data [78]. Unlike the system GMM, the IV-GMM is particularly suited for panel data models, using instrumental variables that are correlated with endogenous explanatory variables but uncorrelated with the error term. This method is adept at handling challenges like measurement errors, reverse causality, and heteroscedasticity, utilizing moment conditions to ensure consistency and reliability [79]. Moreover, the fixed-effects option accounts for unobserved heterogeneity that remains constant over time for each individual. The system GMM method employed in this study can be summarized by the following equation:

$$Depletion_{it} = \alpha_0 + \alpha_1 Depletion_{it-1} + \alpha_2 ECI_{it} + \sum_{h=1}^k \delta_h X_{it} + v_i + \theta_t + \mu_{it} \quad (2)$$

Where $Depletion_{it-1}$ stands for the lagged value of resource depletion, capturing the persistence or delayed effects of past resource depletion on current conditions.

Finally, we use pooled quantile regression to examine the varying effects of economic complexity across different points in the conditional distribution of resource depletion. This method offers a deeper insight into the relationships, especially when the influence of predictors may differ at various quantiles, making it ideal for analyzing data that may have skewness or outliers [80].

4. Results and discussion

It is imperative to check for multicollinearity before moving further with estimations, since its existence will provide spurious findings. To do this, we check for multicollinearity using the Variance Inflation Factors (VIFs) test. As shown in Table 4, all of the VIFs are less than 10 and the tolerance factors (1/VIF) are more than 0.1. These results imply that the explanatory variables' inclusion in the regression model collectively prevented multicollinearity.

4.1. Baseline results

The baseline results presented in Table 5 using the fixed effect Discroll and Kraay indicate a negative association between economic complexity and all four measures of natural resource depletion, with statistically significant effects on energy depletion, mineral depletion, and total natural resource depletion. Although the effect on forest depletion is negative, it is not statistically significant, suggesting that economic complexity may not have a strong direct impact on forest resources. The finding suggest that a unit increase in ECI, holding all else constant, leads to a 1.69 percentage point reduction in energy depletion and a 1.75 percentage point decline in total natural resource depletion, reinforcing the argument that more complex and diversified economies are less reliant on extractive industries. This negative relationship can be explained through the lens of economic transformation and structural upgrading. As economies become more sophisticated, they tend to shift away from primary commodity dependence toward higher-value-added industries that rely less on direct resource extraction. This aligns with the structural transformation hypothesis proposed by Hidalgo and Hausmann [11], which posits that economic complexity fosters innovation, industrial diversification, and a movement toward knowledge-intensive sectors that exert less pressure on natural resources. Additionally, more complex economies often implement stringent environmental regulations, adopt cleaner technologies, and integrate circular economy principles, further reducing resource depletion [10]. The observed negative association may also be linked to the "resource curse" hypothesis [29], where economies overly dependent on natural resources struggle to diversify, whereas those with higher economic complexity experience a smoother transition toward sustainable growth with lower environmental degradation.

Beyond economic complexity, the control variables offer further insights into the drivers of natural resource depletion. In this regard, we control for urbanization, which is positively associated with energy, forest, and mineral depletion, suggesting that rapid urban expansion increases demand for energy, construction materials, and land, thereby intensifying resource extraction [63]. Industrialization exhibits a strong positive impact across all measures of depletion, emphasizing the resource-intensive nature of manufacturing and heavy industries. This aligns with the notion that industrial growth, particularly in developing economies, is often characterized by high energy consumption and raw

Table 4
Variance inflation factor.

	Energy Depletion		Forest Depletion		Mineral depletion		TNRD	
	VIF	1/VIF	VIF	1/VIF	VIF	1/VIF	VIF	1/VIF
Industrialization	2.351	0.425	2.300	0.435	2.352	0.425	2.349	0.426
Urbanization	1.880	0.532	1.877	0.533	1.880	0.532	1.882	0.531
Trade	1.852	0.540	1.821	0.549	1.852	0.540	1.853	0.540
Financial dev	1.498	0.668	1.488	0.672	1.498	0.668	1.509	0.663
ECI	1.487	0.673	1.469	0.681	1.488	0.672	1.492	0.670
Mean VIF	1.814	.	1.791	.	1.814	.	1.817	.

Source: *Author's Construction*

Table 5
Effect of economic complexity on resource depletion-Driscoll & Kraay Estimates.

VARIABLES	(1)	(2)	(3)	(4)
	Energy Depletion	Forest Depletion	Mineral Depletion	Total NRD
ECI	−1.690*** (0.327)	−0.154 (0.331)	−0.275* (0.152)	−1.748*** (0.356)
Urbanization	0.0663*** (0.0228)	0.0386*** (0.0114)	0.0105*** (0.00363)	0.0150 (0.0274)
Industrialization	0.454*** (0.0528)	0.649*** (0.0206)	0.0861*** (0.00892)	0.465*** (0.0379)
Trade	0.0151 (0.0127)	0.0241*** (0.00341)	0.00852* (0.00483)	0.0493*** (0.0126)
Financial dev	−0.0744*** (0.0196)	−0.111*** (0.0190)	−0.0173* (0.00880)	−0.168*** (0.0255)
Constant	−12.15*** (0.918)	6.615*** (0.490)	−0.835*** (0.0306)	−5.665*** (1.189)
Observations	670	683	669	655
R-squared	0.627	0.453	0.435	0.616
Number of groups	29	29	29	29

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

Source: *Author's construction*.

material extraction, contributing to environmental stress [64]. We also control for Trade openness which shows a significant positive associations with forest, mineral, and total natural resource depletion. This could be attributed to increased demand for primary commodities in global markets, driving deforestation, mining, and overall resource extraction [66]. On the other hand, controlling for financial development exerts a mitigating effect, as evidenced by its negative and significant association with all depletion measures. This suggests that well-functioning financial markets facilitate investments in cleaner technologies, resource-efficient production processes, and sustainable business practices, which help curb excessive resource exploitation [67].

The findings contribute important insights to the literature by empirically linking economic complexity to reductions in natural resource depletion, particularly in the Sub-Saharan African context where dependence on primary commodities remains high. While existing studies have emphasized the role of economic diversification in mitigating resource dependence [31,81], limited empirical work has examined how complexity, as measured by the Economic Complexity Index, directly influences resource depletion. The observed negative association between economic complexity and depletion of energy, mineral, and total natural resources underscores the transformative potential of economic sophistication in fostering sustainable growth pathways. This provides evidence that countries which diversify into more knowledge-intensive sectors may be able to escape the constraints of the resource curse, offering a concrete mechanism through which structural transformation alleviates environmental pressures [11,82]. By showing that complexity reduces reliance on extractive activities, the study advances the literature beyond broad debates on resource dependence and sustainability, highlighting a novel empirical channel linking industrial upgrading and environmental outcomes in resource-rich economies.

The control variable results also yield significant implications for the broader discourse on development-environment trade-offs in Sub-Saharan Africa. The positive associations of urbanization, industrialization, and trade openness with resource depletion reinforce the established argument that rapid growth in these areas, when unaccompanied by sustainability frameworks, can exacerbate environmental degradation [64]. Yet, the mitigating effect of financial development introduces a nuanced perspective, suggesting that access to finance can serve as an enabling factor for green investment and resource-efficient technologies, consistent with findings by Zafar et al. [83]. This complements the complexity-depletion nexus by showing that both structural upgrading and financial deepening can jointly contribute to reducing environmental pressures in developing economies. These results enrich the literature by illustrating that while traditional growth drivers intensify depletion, economic complexity and financial development may provide sustainable exit strategies. This dual perspective is particularly novel in the SSA context, where the intersection of industrial policy, financial development, and environmental sustainability remains underexplored.

Although the baseline results in Table 5 provide statistically significant estimates, there remains a risk of endogeneity bias, particularly due to potential reverse causality between economic complexity and natural resource depletion. If causality runs in both directions, the estimated coefficients may be inconsistent and unreliable, thus weakening the robustness of the Driscoll and Kraay results. To address this concern, the empirical literature suggests various strategies, including instrumental variable (IV) techniques and dynamic panel estimators. This study prioritizes the use of internal instruments through the two-step system GMM, a widely adopted approach for handling endogeneity in dynamic panel data models. The results from the sGMM estimation are presented in Table 6, where we first conduct diagnostic tests to validate the empirical findings. The Arellano-Bond AR(1) and AR(2) tests confirm that while first-order serial correlation is present, there is no second-order serial correlation in the first-differenced residuals, ensuring that the moment conditions used in estimation remain valid. Additionally, the Hansen test of over-identifying restrictions is insignificant, indicating that the chosen instruments satisfy the exogeneity condition, as required for consistent parameter estimates. As Hansen [84] asserts, valid instruments should be correlated with the endogenous regressors while remaining uncorrelated with the error term. Furthermore, the sGMM estimates for the lagged dependent variable are statistically significant at the 1 % level and below 1, reinforcing the dynamic nature and persistence of resource depletion over time. Collectively, these post-estimation diagnostics confirm the validity of the sGMM results in Table 6, strengthening the reliability of our empirical findings.

Regarding the estimated coefficients, the results from the two-step system GMM reaffirm the earlier findings that economic complexity plays an important role in mitigating natural resource depletion. Specifically, the coefficient of ECI remains negative and statistically significant across all four measures of resource depletion, reinforcing the argument that greater economic sophistication and diversification contribute to sustainable resource use. Quantitatively, a unit increase in ECI, holding all other factors constant, leads to a reduction in energy

Table 6
Effect of economic complexity on resource depletion-sGMM estimates.

VARIABLES	(1)	(2)	(3)	(4)
	Energy Depletion	Forest Depletion	Mineral Depletion	Total NRD
L.Energydepletion	0.893*** (0.0118)			
L.Forestdepletion		0.856*** (0.0201)		
L.Mineraldepletion			0.953*** (0.0353)	
L.TNRD				0.895*** (0.0152)
ECI	−0.511*** (0.0360)	−0.219*** (0.0225)	−0.430*** (0.0936)	−0.629*** (0.0495)
Urbanization	0.0535*** (0.0106)	0.0586*** (0.0134)	0.0180*** (0.00259)	0.106*** (0.0242)
Industrialization	0.422*** (0.0222)	0.0204** (0.00870)	0.0266*** (0.00477)	0.484*** (0.0352)
Trade	0.0500*** (0.0102)	0.0337*** (0.00602)	0.0117*** (0.00362)	0.0114 (0.0165)
Financial dev	−0.0281*** (0.00552)	−0.0545*** (0.00272)	−0.0145*** (0.00219)	−0.0553*** (0.00767)
Year FE	Yes	Yes	Yes	Yes
Constant	−3.547*** (0.583)	5.023*** (0.877)	−1.043*** (0.290)	−2.888** (1.114)
Observations	644	657	643	629
Number of id	33	33	33	33
AR(1)	0.0237	0.0191	0.0232	0.00494
AR(2)	0.271	0.119	0.112	0.209
Hansen OIR	0.958	0.914	0.990	0.935
Instruments	24	24	24	24

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

Source: *Author's construction.*

depletion by approximately 0.511 units, forest depletion by 0.219 units, mineral depletion by 0.430 units, and total natural resource depletion by 0.629 units. These effects are all statistically significant at the 1 % level, lending strong empirical support to the hypothesis that rising economic complexity curbs resource depletion in SSA. The magnitude of these estimates suggests that as countries shift towards more diversified and technologically advanced production structures, their dependence on extractive activities diminishes, leading to a substantial decline in resource depletion. This emphasizes the importance of policies that foster industrial upgrading, knowledge-intensive sectors, and higher-value-added production as pathways toward sustainable development. Moreover, the estimated coefficients of the control variables maintain their expected signs, further confirming the robustness of our initial results. Overall, our findings corroborates those of Ul-Durar et al. [24], Li et al. [25] and Kelly et al. [1].

4.2. Robustness checks

In this subsection, we outline the results from various robustness checks. First, we include 5- and 10-year lags of ECI as explanatory variables. Second, we add a new set of control variables. Third, we employ an alternative measure of economic complexity. Next, we examine the effect of different resource rents on the relationship and lastly, we apply alternative estimation methods.

4.2.1. Robustness to the use of 5- and 10-year lags

Previous results consistently indicate that ECI in a given year reduces resource depletion within the same period. However, this finding implicitly assumes that the effect of ECI on resource depletion is immediate, which may not fully capture the dynamics of economic transformation. Intuitively, the relationship between ECI and resource depletion operates through several intermediary channels, such as technological advancements, income growth, and institutional improvements, all of which take time to manifest. To address this concern, we conduct a robustness check by introducing five-year and ten-year

lags of ECI to examine whether its impact on resource depletion persists over time. The results from this analysis are presented in Table 7, with columns (1) to (4) displaying the estimates for the five-year lag and columns (5) to (8) showing the results for the ten-year lag. Notably, the findings remain consistent, demonstrating that lagged ECI continues to exhibit a negative and statistically significant association with all measures of resource depletion. This suggests that as countries enhance their economic complexity, the long-term effects of structural transformation gradually materialize, further reinforcing the role of economic sophistication in reducing resource depletion. Additionally, the estimated coefficients for the control variables maintain their expected signs, confirming the robustness of our previous results.

4.2.2. Robustness to additional control variables

We further test the robustness of our results by incorporating additional control variables into the baseline model, specifically military expenditure, inflation, and control of corruption. The results of this exercise, presented in Table 8, continue to reinforce our main findings. The coefficients associated with economic complexity remain negative and statistically significant across all measures of resource depletion, corroborating the conclusion that rising economic complexity systematically reduces resource depletion. Interestingly, the additional control variables exhibit mixed effects on resource depletion.

Military expenditure and control of corruption are negatively and significantly associated with resource depletion, suggesting that higher military spending and stronger institutional quality contribute to better environmental outcomes. Military presence, particularly in resource-rich areas, may serve as a deterrent against illegal activities such as unauthorized logging, unregulated mining, and poaching, thereby reducing environmental and resource degradation [85]. Similarly, improved governance through better control of corruption fosters a more transparent and accountable management of natural resources, ensuring that resource revenues are channeled into productive investments rather than lost to rent-seeking and misallocation. This aligns with the argument that strong institutions create an enabling

Table 7
Robustness 5- and 10-year lags.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Energy Depletion	Forest Depletion	Mineral Depletion	Total NRD	Energy Depletion	Forest Depletion	Mineral Depletion	Total NRD
L.Energydepletion	0.730*** (0.0179)				0.799*** (0.0167)			
L.Forestdepletion		0.751*** (0.00972)				0.778*** (0.0210)		
L.Mineraldepletion			0.872*** (0.0414)				0.893*** (0.0249)	
L.TNRD				0.833*** (0.0256)				0.875*** (0.0171)
ECI_5	−1.435*** (0.310)	−0.744*** (0.116)	−0.117* (0.0974)	−1.406** (0.617)				
ECI_10					−0.163* (0.0993)	−0.810*** (0.136)	−0.113*** (0.0247)	−0.890*** (0.270)
Urbanization	0.0750*** (0.0177)	0.0262 (0.0158)	0.0343*** (0.0105)	0.0253* (0.0126)	0.0136 (0.00899)	0.00526 (0.0114)	0.0151* (0.00799)	0.0426* (0.0225)
Industrialization	0.235*** (0.0346)	0.0356*** (0.00937)	0.0544*** (0.00936)	0.347*** (0.0238)	0.210*** (0.0141)	0.0114 (0.00765)	0.0319*** (0.00945)	0.366*** (0.0305)
Trade	0.0495*** (0.00896)	0.0396*** (0.00566)	0.0184*** (0.00423)	0.00630 (0.0165)	0.0106** (0.00453)	0.0153*** (0.00259)	0.0371*** (0.00186)	0.0184 (0.0114)
Financial dev	−0.124*** (0.0168)	−0.0400*** (0.00918)	−0.0370*** (0.00591)	−0.121*** (0.0136)	−0.0416*** (0.00931)	−0.0551*** (0.00685)	−0.0117 (0.00954)	−0.0744*** (0.0208)
Constant	−2.791*** (0.711)	2.950*** (0.388)	−1.444*** (0.425)	−1.948 (1.160)	−3.135*** (0.508)	1.956*** (0.438)	−0.217* (0.126)	−3.113** (1.318)
Observations	627	610	606	606	537	550	536	526
Number of id	33	33	33	33	33	33	33	33
AR(1)	0.0486	0.0165	0.0358	0.0498	0.0395	0.0130	0.0341	0.0190
AR(2)	0.277	0.273	0.284	0.129	0.106	0.392	0.170	0.424
Hansen OIR	0.855	0.800	0.737	0.750	0.553	0.667	0.530	0.602
Instruments	29	29	29	29	24	24	24	24

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

Source: *Author's construction.*

Table 8
Robustness to additional covariates.

VARIABLES	(1)	(2)	(3)	(4)
	Energy Depletion	Forest Depletion	Mineral Depletion	Total NRD
L.Energydepletion	0.840*** (0.0209)			
L.Forestdepletion		0.823*** (0.0257)		
L.Mineraldepletion			0.749*** (0.0448)	
L.TNRD				0.886*** (0.0285)
ECI	−0.732*** (0.177)	−0.158** (0.0763)	−0.620*** (0.122)	−0.566* (0.293)
Urbanization	0.00534 (0.0113)	0.0253*** (0.00876)	0.0116*** (0.00288)	0.0312 (0.0245)
Industrialization	0.347*** (0.0261)	−0.0530*** (0.00848)	0.00832* (0.00456)	0.328*** (0.0303)
Trade	0.0139* (0.00684)	0.00378 (0.00241)	0.0126*** (0.00245)	0.0298*** (0.00569)
Financial dev	−0.0291*** (0.00524)	−0.0217*** (0.00320)	−0.0287*** (0.00359)	−0.0347** (0.0138)
Military exp	−0.372*** (0.0607)	−0.0851* (0.0745)	−0.500*** (0.0855)	−0.254*** (0.0845)
Inflation	0.0863*** (0.00143)	0.0115*** (0.00218)	0.0331*** (0.00433)	0.0429*** (0.00236)
Control of Corruption	−1.948*** (0.403)	−0.412* (0.217)	−0.186 (0.112)	−2.849*** (0.744)
Year FE	Yes	Yes	Yes	Yes
Constant	−6.540*** (0.427)	−0.948* (0.470)	−0.817*** (0.290)	−5.674*** (1.054)
Observations	639	623	641	619
Number of id	33	33	33	33
AR(1)	0.0144	0.00967	0.0312	0.0181
AR(2)	0.166	0.179	0.169	0.157
Hansen OIR	0.600	0.609	0.688	0.530
Instruments	31	31	31	31

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

Source: *Author's construction.*

environment for sustainable resource management [86]. Conversely, inflation exerts a positive and significant effect on resource depletion, indicating that rising inflationary pressures may accelerate natural resource exploitation. High inflation erodes the real value of money, increases economic uncertainty, and discourages long-term investment in sustainable industries. As a result, firms and governments may prioritize short-term gains by intensifying resource extraction to hedge against inflation-induced losses [87,88]. Regarding the baseline control variables, they maintain their expected signs, consistent with previous results, further validating the robustness of our findings. Therefore, we can conclude that our core results remain stable and resilient to the inclusion of additional control variables.

4.2.3. Robustness to an alternative measure of ECI

Building on the recent work of Stojkoski et al. [61], we incorporate an alternative measure of economic complexity—technology complexity (ECI-Tech)—to further test the robustness of our findings. This metric captures the sophistication of a country's technological capabilities, offering a more granular perspective on the role of innovation and knowledge-intensive industries in economic transformation. The results, presented in Table 9, reveal that ECI-Tech exhibits a negative and statistically significant effect on all measures of resource depletion, reinforcing our initial hypothesis. This suggests that economies with more advanced technological capabilities are better positioned to transition away from resource-intensive activities toward high-value-added sectors, leading to a decline in natural resource depletion. The persistence of this negative relationship, even when substituting ECI with ECI-Tech, highlights the robustness of our findings as well as the role of technological sophistication in fostering sustainable resource management. These results provide further evidence that economic complexity, whether measured through trade-based product sophistication or technology-driven innovation, plays an important role in mitigating resource depletion in SSA.

4.2.4. Robustness to alternative estimation techniques

Previous results from the system GMM provide compelling evidence supporting the hypothesis that rising economic complexity helps mitigate resource depletion in SSA. However, despite its widespread use in dynamic panel data analysis, the system GMM has been subject to criticism in the empirical literature, particularly concerning instrument proliferation and potential weak instrument bias, which can undermine the reliability of estimated coefficients [89]. To address these concerns and further validate our findings, we propose two alternative estimation techniques: the IV-GMM and quantile regression. IV-GMM is particularly useful in addressing potential endogeneity issues by employing external instruments that satisfy both relevance and exogeneity conditions, thereby providing more robust estimates [90]. Meanwhile, quantile regression allows us to examine the heterogeneous effects of economic complexity across different levels of resource depletion, offering an understanding of how ECI influences natural resource dynamics beyond the conditional mean [80]. The IV-GMM estimation results, presented in Table A2 of the Appendix, further validate our main findings.

The quantile regression results, presented in Table 10, provide deeper insights into how the relationship between ECI and resource depletion varies across different levels of resource depletion in SSA. The results show that ECI consistently exhibits a negative and statistically significant effect across all quantiles, though the magnitude of the effect diminishes as resource depletion increases. Specifically, the coefficient of ECI is strongest at the 10th quantile and 25th quantile, suggesting that in countries with lower levels of resource depletion, economic complexity plays a substantial role in curbing resource exploitation. However, the effect weakens at higher quantiles, with the coefficient declining to -0.755 at the median, -0.104 at the 75th quantile, and -0.253 at the 90th quantile. This pattern, visually illustrated in Fig. 4, suggests that while ECI remains an important determinant of resource sustainability, its influence is more pronounced in economies with relatively lower levels of resource depletion.

Table 9
Alternative measure of economic complexity (Technology ECI).

VARIABLES	(1) Energy Depletion	(2) Forest Depletion	(3) Mineral Depletion	(4) Total NRD
L.Energydepletion	0.820*** (0.0157)			
L.Forestdepletion		0.863*** (0.0217)		
L.Mineraldepletion			0.844*** (0.0392)	
L.TNRD				0.917*** (0.0155)
ECI_Tech	−0.230* (0.126)	−0.795*** (0.0454)	−0.107** (0.0470)	−0.0672** (0.0185)
Urbanization	0.0247 (0.0147)	0.0541*** (0.0153)	0.0229*** (0.00394)	0.0954*** (0.0224)
Industrialization	0.354*** (0.0380)	0.0178** (0.00772)	0.0341*** (0.00513)	0.483*** (0.0379)
Trade	0.0515*** (0.0152)	0.0387*** (0.00358)	0.0228*** (0.00232)	0.0188* (0.00986)
Financial dev	−0.0246*** (0.00701)	−0.0508*** (0.00325)	−0.0192*** (0.00201)	−0.0568*** (0.00492)
Year FE	Yes	Yes	Yes	Yes
Constant	−2.961*** (0.635)	4.222*** (0.661)	−1.438*** (0.211)	−3.503*** (1.178)
Observations	644	657	643	629
Number of id	33	33	33	33
AR(1)	0.0195	0.0253	0.0225	0.00527
AR(2)	0.222	0.131	0.286	0.317
Hansen OIR	0.988	0.908	0.956	0.978
Instruments	24	24	24	24

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

Source: Author's construction.

Table 10
Quantile regressions.

VARIABLES	Quantile 10	Quantile 25	Median 50	Quantile 75	Quantile 90
	Dependent Variable: Total NRD				
	(1)	(2)	(3)	(4)	(5)
ECI	−2.742*** (0.535)	−2.686*** (0.453)	−0.755*** (0.0801)	−0.104* (0.0665)	−0.253* (0.139)
Urbanization	0.0448** (0.0199)	0.0479*** (0.0169)	0.0190 (0.0298)	0.00446 (0.0247)	−0.00541 (0.0387)
Industrialization	0.147*** (0.0303)	0.264*** (0.0256)	0.453*** (0.0453)	0.523*** (0.0376)	0.570*** (0.0588)
Trade	0.0271** (0.0129)	0.0330*** (0.0110)	0.0499** (0.0194)	0.0822*** (0.0161)	0.0770*** (0.0251)
Financial dev	−0.101*** (0.0195)	−0.102*** (0.0165)	−0.180*** (0.0292)	−0.187*** (0.0242)	−0.219*** (0.0378)
Constant	−5.715*** (0.904)	−7.606*** (0.765)	−5.218*** (1.354)	−2.891** (1.123)	0.600** (0.355)
Observations	655	655	655	655	655

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

Source: Author's construction.

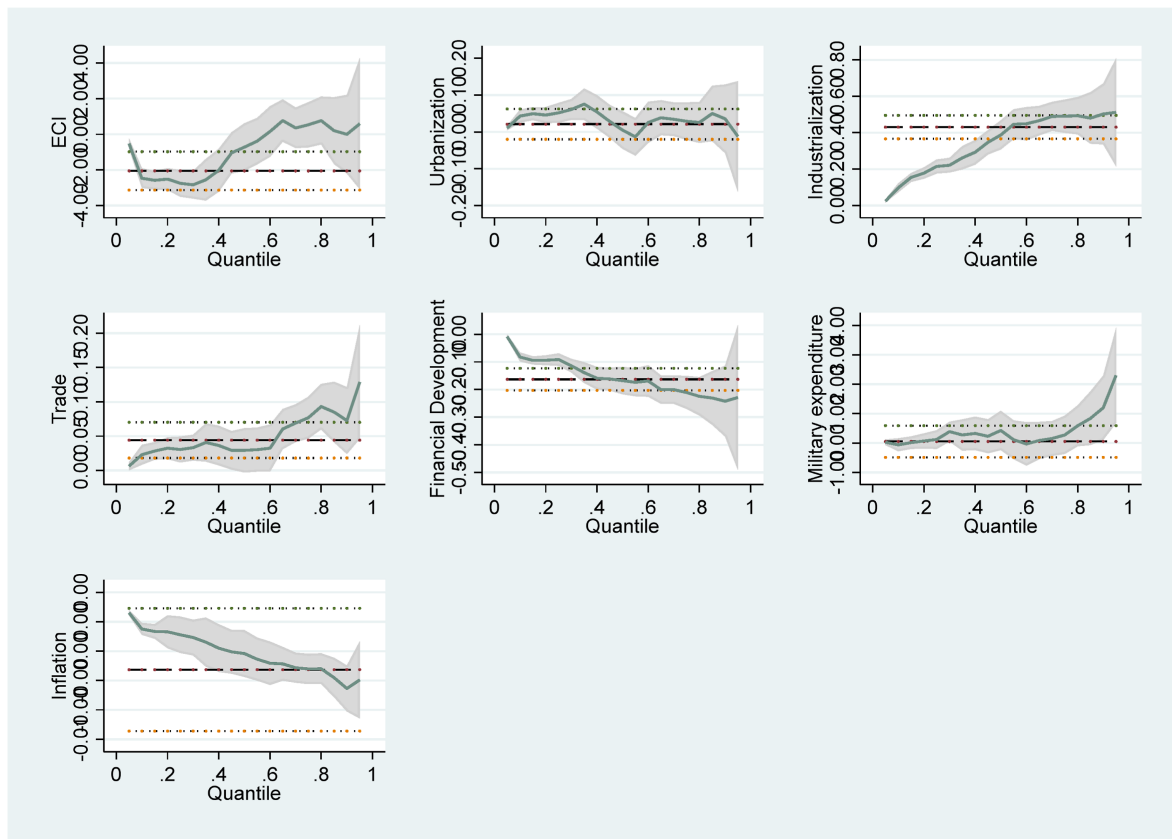


Fig. 4. Quantile effects on Resource Depletion. Source: Author's Construction.

4.3. Analyses of transmission channels

The transmission mechanisms between economic complexity and resource depletion are theoretically discussed in Sub-section 2.2. In this sub-section, we empirically analyze these mechanisms to better understand how economic complexity influences resource depletion. Specifically, we focus on two key channels: the internet channel and the income channel, both of which have been identified as potential pathways in the prior theoretical discussion. The empirical analysis follows the methodology outlined in Equations (4) and (5), with the framework illustrated in Fig. 5.

$$\begin{cases} \text{Model 1 : } Med_{it} = \alpha_1 + b_1 ECI_{it} + \delta_h X_{it} + \mu_{it} \\ \text{Model 2 : } Depletion_{it} = \alpha_2 + b_2 ECI_{it} + b_3 Med_{it} + \delta_h X_{it} + v_{it} \end{cases} \quad (3)-(4)$$

Where Med_{it} represents the mediating variable, which can be either the internet, or income. The parameter δ_h captures the indirect effect of economic complexity on resource depletion. All other terms retain the same definitions as in Equation (2). One key advantage of employing a system of simultaneous equations is its ability to establish causal relationships between variables and to decompose their effects into direct and indirect components. Additionally, the Sobel [91] test is used to determine the presence of mediation. Specifically, this test evaluates

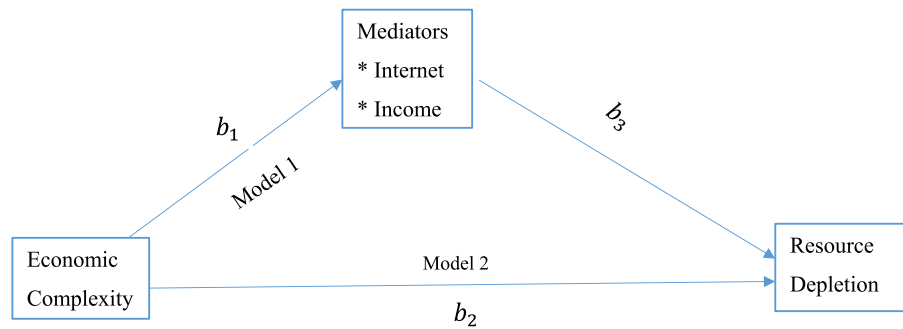


Fig. 5. ECI and Resource Depletion: transmission mechanisms.
Source: *Author's Construction*.

whether introducing a mediating variable significantly diminishes the indirect effect of the primary independent variable on the dependent variable. Results for this exercise are reported in [Table 11](#).

The estimation process of [Fig. 5](#) is outlined as follows. Initially, we estimate Model (1) or Equation (3) by regressing ECI on the mediators to obtain b_1 . In the next step, we estimate Equation (4) by regressing ECI on Total NRD while controlling for the mediators, which provides us with b_2 and b_3 . The indirect effect is calculated as the product of b_1 and b_3 . This value also indicates the size of the mediation effect, which depends on how economic complexity affects the mediators (b_1) and how these mediators, in turn, affect resource depletion (b_3).

Columns (1) and (3) of [Table 11](#) present the estimates for model (1), where the internet and income respectively serve as mediators in the relationship between ECI and total resource depletion. The results show that ECI significantly influences both mediators, with coefficients statistically significant at the 1 % level. This suggests that as economic complexity increases, there is a corresponding rise in internet penetration and income levels, which are essential channels through which structural transformation occurs. In columns (2) and (4), where the mediators are included as control variables, their effects on resource depletion become evident. Both the internet and income channels significantly influence total resource depletion, further confirming their role in shaping environmental outcomes. Finally, column (5) of [Table 11](#) displays the total effect of ECI on total resource depletion when the mediators are excluded, showing that ECI remains a significant determinant of resource depletion.

From an economic perspective, internet penetration and income levels can mediate the relationship between economic complexity and

resource depletion by influencing technological innovation, production efficiency, and consumption patterns. Greater internet access facilitates knowledge diffusion, enabling firms to adopt resource-efficient technologies and shift towards high-value, low-extraction industries [92]. Similarly, rising income levels can drive structural transformation, where economies transition from resource-intensive activities to service and knowledge-based sectors, thereby reducing direct resource depletion [93].

To assess whether the indirect effect of ECI through the internet and income is statistically significant, mediation tests are conducted. The Sobel test statistic is computed to evaluate the mediation effects of both channels, with the null hypothesis stating that there is no mediation. The results confirm that the indirect effects are significantly different from zero, suggesting that both internet penetration and income levels serve as meaningful transmission mechanisms in the relationship between economic complexity and resource depletion. Additionally, to ensure the robustness of these findings, we employ the Delta and Monte Carlo tests as alternative mediation approaches. The conclusions remain unchanged even when bootstrap confidence intervals are applied, further validating the statistical significance of the mediation effects. Overall, the findings indicate that the internet mediates approximately 13 % of the total effect of ECI on total resource depletion, while income accounts for about 19 %, indicating the importance of these channels in explaining how economic sophistication influences resource sustainability.

Beyond the empirical findings, this study makes a conceptual contribution by clarifying the economic complexity–resource depletion nexus as a dynamic, bidirectional, and institutionally conditioned

Table 11
Empirical analyses of Transmission Channels.

	Internet channel		Income Channel		Total effect ECI
	Internet	TNRD	Income	TNRD	
ECI	4.5040*** (0.968)	−7.5513*** (0.649)	0.3047*** (0.057)	−8.1853*** (0.693)	−2.263*** (0.591)
Internet		−0.0676*** (0.018)			
Income				1.4002*** (0.440)	
Baseline Controls	Yes	Yes	Yes	Yes	Yes
Constant	14.3260*** (1.236)	1.9575*** (0.573)	7.2884*** (0.065)	−9.0887*** (3.392)	−2.723*** (0.811)
Observations	762	762	778	778	778
Sobel	0.304*** (0.000)		0.427*** (0.003)		
Delta	0.304*** (0.004)		0.427*** (0.006)		
Monte Carlo	0.304*** (0.004)		0.428*** (0.006)		
% of the total effect mediated	13		19		

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

Source: *Author's construction*.

relationship. The nexus perspective advances understanding beyond the notion that increasing economic complexity automatically leads to lower resource pressure. Instead, it emphasizes that the effect of complexity depends on *how* economies diversify, *what* capabilities they accumulate, and *which* sectors drive structural transformation. When complexity arises through innovation, knowledge diffusion, and movement into higher value-added manufacturing and services, it can reduce reliance on extractive sectors. However, when diversification proceeds within resource-intensive or energy-heavy industries, complexity may scale up extraction and environmental pressure. Likewise, resource depletion feeds back into complexity trajectories where unsustainably rapid extraction can weaken institutional capacity, discourage productive learning, and entrench commodity dependence, whereas effectively managed resource rents can finance education, technological upgrading, and industrial capabilities that support diversification. These feedback loops and strategic pathways provide a lens for understanding why some resource-rich economies diversify successfully while others remain locked in extractive patterns. This perspective makes explicit that structural transformation is not purely an economic outcome but a governance and capability-building process, which is important for interpreting Africa's development challenges and opportunities.

5. Conclusion and policy recommendations

Addressing resource depletion in SSA is essential for safeguarding the region's development trajectory and achieving global sustainability goals, particularly given SSA's heavy reliance on natural resources for economic growth, industrialization, and livelihood sustenance. The region faces mounting challenges as far as resource depletion is concerned, which threaten progress toward the Sustainable Development Goals (SDGs), especially Goal 12 on responsible consumption and production, and Goal 15 on life on land. Overexploitation of these resources not only depletes the region's natural capital but also exacerbates environmental degradation, biodiversity loss, and socio-economic vulnerabilities. Economic complexity offers a strategic lever for addressing these challenges by fostering structural transformation, industrial diversification, and innovation-driven growth, which reduce reliance on resource-intensive sectors and promote sustainable economic pathways. Building on this foundation, this study investigates the effect of economic complexity on resource depletion, specifically energy depletion, forest depletion, and mineral depletion in 33 SSA countries over the period 1998–2022, providing a comprehensive assessment of how economic sophistication influences resource sustainability. The study employs a wide range of estimation techniques, including the fixed-effects Driscoll and Kraay estimator, the two-step system GMM, the IV-GMM, and quantile regression. The findings provide compelling evidence that economic complexity significantly reduces resource depletion in SSA,

reinforcing the argument that higher levels of product sophistication and technological advancement enable economies to shift toward less extractive and more sustainable industrial activities. Notably, the study highlights the role of the internet and income as key transmission channels through which economic complexity influences resource depletion. These results remain robust under various sensitivity tests, are resilient to endogeneity concerns, and hold true across different metrics of economic complexity.

Based on the findings, policymakers should prioritize strategies that enhance economic diversification and technological advancement, such as investing in high-value manufacturing, innovation-driven industries, quality of institutions, and skills development including human capital to accelerate the structural transformation away from resource dependence. Given that urbanization, industrialization, and trade openness contribute to resource depletion, governments should implement stricter environmental regulations, promote sustainable industrial practices, and incorporate green trade policies to balance economic growth with resource conservation. Additionally, financial development has been shown to mitigate resource depletion, highlighting the need for policies that strengthen financial markets, encourage green financing, and support investments in renewable energy and sustainable resource management. Since the internet and income have been identified as potential channels through which economic complexity mitigates resource depletion, expanding digital infrastructure and improving income distribution through inclusive economic policies can enhance the effectiveness of economic complexity in promoting resource sustainability.

While this study highlights the role of economic complexity in reducing resource depletion in SSA, it is limited by its reliance on macroeconomic data, which may overlook country-specific institutional and policy differences. Future research could incorporate micro-level data and case studies to better capture these effects on resource management.

Data availability statement

The data underlying this article will be shared on request.

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Declaration of competing interest

The author declares no real, potential, or apparent conflict of interest.

Appendix

Table A1
Fan et al. [94], and Pesaran [95,96] tests of weakly cross-sectional dependence

	Testing for weak cross-sectional dependence (CSD)	
	H0: weak cross-section dependence	H1: strong cross-section dependence
	CD	CDw+
Energy Depletion	12.390 (0.000)	563.720 (0.000)
Forest Depletion	22.460 (0.000)	709.410 (0.000)
Mineral Depletion	32.710 (0.000)	803.940 (0.000)

(continued on next column)

Table A1 (continued)

	Testing for weak cross-sectional dependence (CSD)	
	H0: weak cross-section dependence	H1: strong cross-section dependence
	CD	CDw+
TNRD	30.530 (0.000)	1116.970 (0.000)
ECI	2.100 (0.035)	453.700 (0.000)
Urbanization	97.590 (0.000)	2507.390 (0.000)
Industrialization	4.570 (0.000)	1040.560 (0.000)
Trade	14.830 (0.000)	802.140 (0.000)
Financial dev	30.890 (0.000)	1023.740 (0.000)

Notes: p-values in parenthesis. CD and CDw + refer to Cross-sectional Dependence test associated to Pesaran [95,96] and Fan et al. [94], respectively.

Source: *Author's construction*

Table A2
IV-GMM Estimates

VARIABLES	(1)	(2)	(3)	(4)
	Energy Depletion	Forest Depletion	Mineral Depletion	Total NRD
ECI	−1.194* (0.619)	−0.371*** (0.0994)	−0.442** (0.191)	−2.277*** (0.495)
Urbanization	0.0991*** (0.0340)	0.155*** (0.0162)	0.0743** (0.0339)	0.188*** (0.0354)
Industrialization	0.304*** (0.0436)	0.115*** (0.0135)	0.0665*** (0.0100)	0.256*** (0.0536)
Trade	0.0495*** (0.0108)	0.00573 (0.00351)	0.0110** (0.00448)	0.0627*** (0.00788)
Financial dev	−0.397*** (0.0259)	−0.666*** (0.0317)	−0.0119** (0.00480)	−0.0938** (0.0189)
Observations	639	652	638	625
R-squared	0.406	0.492	0.526	0.460
Number of id	33	33	33	33
Hansen (P-value)	0.444	0.408	0.405	0.522
Fisher (P-value)	0.000	0.000	0.000	0.000

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

Source: *Author's construction*.

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