The Moderating Role of Urbanisation in the Environmental Impact of Economic Complexity and Capital Formation: Evidence from OECD Countries

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Abstract

Environmental degradation remains a pressing challenge for high-income countries as they strive to balance economic growth with ecological sustainability. While previous studies have examined various drivers of environmental outcomes, the interplay between economic complexity, capital formation, and energy use has received limited attention. This study investigates how these factors influenced ecosystem vitality in high-income countries over the period of 2000–2022. Drawing on Ecological Modernisation Theory and the Environmental Kuznets Curve framework, this study employs four panel data estimation methods, Panel-Corrected Standard Errors, Driscoll–Kraay Estimators, Poisson Pseudo-Maximum Likelihood, and Feasible Generalised Least Squares, to address cross-sectional dependence, heteroskedasticity, and potential non-linearities. The analysis reveals three key findings. First, while economic complexity improves ecosystem vitality, this benefit weakens substantially in highly urbanised contexts, indicating diminishing returns to knowledge spillovers in dense urban environments. Second, urbanisation significantly reduces the negative environmental impacts of capital accumulation, suggesting that urban agglomeration enables more sustainable infrastructure deployment. Third, the urbanisation–environment relationship follows an inverted U-shape, with environmental pressures peaking at intermediate development stages before improving in advanced urban systems. Additionally, renewable energy adoption consistently improves ecosystem vitality, whereas energy intensity exerts negative effects, highlighting the urgency of comprehensive energy transition strategies. These findings demonstrate that urbanisation acts not as a uniform force, but as a dynamic variable requiring spatially differentiated strategies: governance and infrastructure optimisation in dense urban cores, complexity-driven innovation in peri-urban regions, and energy-intensity regulations across all development stages. These findings point to an integrated policy framework that addresses (1) density-sensitive economic complexity, (2) circular infrastructure investment, (3) institutional capacity building, and (4) multi-scalar energy transitions to better align urban development with environmental sustainability.

Key words

urbanisation, economic complexity, ecosystem vitality, energy intensity, renewable energy.

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Introduction

Urbanisation has emerged as one of the most powerful forces shaping environmental sustainability in the 21st century. Beyond physical and spatial transformation, it has the potential to restructure economic systems, energy frameworks, and natural resource use (Zou et al., 2022; Voukkali et al., 2024). Particularly in advanced economies, urban growth not only drives economic expansion but also transforms environmental outcomes through knowledge-intensive production, infrastructure investments, and the diffusion of eco-friendly technologies. Recent studies have demonstrated that rapid urbanisation significantly impacts ecosystem service values, with population density and economic growth being key factors influencing these services (Liu et al., 2020). However, these positive effects are not universal. Unplanned and rapid urbanisation can lead to increased air and water pollution, habitat destruction, and higher carbon emissions (McGranahan et al., 2007; Zhang et al., 2022). Thus, the environmental consequences of urbanisation depend not only on its scale but also on its quality and the structure of accompanying economic systems.

Recent research highlights that indicators such as economic complexity, which reflect the knowledge and technological intensity of a country's production structure, play a key role in determining environmental outcomes (Hidalgo & Hausmann, 2009; Mealy & Teytelboym, 2022). Countries with higher economic complexity are believed to possess the potential to enhance environmental sustainability through high-value-added and resource-efficient production processes (Romero & Gramkow, 2021; Balsalobre-Lorente et al., 2023). Further evidence suggests that advancements in economic complexity contribute to fostering sustainable environmental practices by facilitating cleaner production technologies and innovation-driven growth (Hassan et al., 2023; Salvati & Carlucci, 2020). However, the relationship is not necessarily linear. In lower- and middle-income countries, rising complexity is often accompanied by industrial expansion and the growth of energy-intensive sectors, which in turn accelerates environmental degradation (Aluko et al., 2023; Doğan et al., 2019). Therefore, factors such as the sectoral structure of production and the composition of energy use play a crucial role in shaping the environmental impact of economic complexity.

In this regard, urbanisation should not be treated solely as an independent variable but rather as a moderator that conditions the environmental effects of structural factors such as economic complexity, capital formation, and energy use (Mol & Spaargaren, 2000; Chang et al., 2024). While extensive research has explored the direct environmental impacts of urbanisation, far less attention has been given to how urban settings interact with other structural drivers. Much of the existing literature examines the relationship between economic complexity and environmental performance within a linear and isolated framework (Romero & Gramkow, 2021; Boleti et al., 2021; Doğan et al., 2019), often neglecting the potential moderating role of spatial structures such as urbanisation. Similarly, although the environmental effects of capital formation and energy use are well-documented (Prakash & Sethi, 2023; Liang et al., 2024), there is still limited empirical understanding of how urbanisation may moderate these influences. Recent studies (Prakash & Sethi, 2023; Liang et al., 2024) reinforce the notion that fixed capital formation and energy consumption generally intensify carbon emissions, underscoring the need for integrated green infrastructure planning in urban environments. As is stressed here, while previous research has highlighted these drivers individually, there is a critical gap in understanding how urbanisation interacts with economic complexity and resource intensity in shaping environmental outcomes. Most existing models overlook the spatial–demographic context, thereby underestimating structural heterogeneity across high-income countries. This study addresses this empirical and theoretical gap by conceptualising urbanisation not merely as a background condition, but as a dynamic moderator of structural–environmental linkages. Addressing this gap is particularly crucial for formulating policy strategies aligned with the Sustainable Development Goals (SDGs). Considering the inherent advantages of urban areas, such as fostering knowledge creation, accelerating technological diffusion, and supporting advanced infrastructure, there is a strong theoretical and practical rationale for examining the moderating role of urbanisation through both conceptual frameworks and empirical analysis.

Building on this rationale, this study constructs a theoretical framework inspired by the extended growth model of Mankiw et al. (1992), integrating urbanisation and economic complexity as additional structural variables. Drawing on the innovation-oriented sustainability perspective of Ecological Modernisation Theory and the nonlinearity hypothesis of the Environmental Kuznets

Curve (EKC), the model posits that environmental improvement can be actively achieved through technological progress, institutional reform, and social innovation (Mol & Spaargaren, 2000). In this context, urban settings offer transformative potential through concentrated infrastructure, knowledge flows, and governance mechanisms. Meanwhile, the EKC framework suggests that environmental pressures may initially worsen but later improve as economies reach higher development thresholds. This study investigates whether urbanisation follows a similar nonlinear pattern in its impact on ecosystem outcomes.

Using panel data for OECD countries from 1995 to 2022, the model tests how urbanization moderates the environmental effects of both economic complexity and capital formation. It incorporates interaction terms and quadratic specifications to capture threshold effects. Additionally, the role of energy intensity and renewable energy use is considered to evaluate how shifts in energy composition affect environmental performance. The empirical analysis employs multiple robust estimation techniques to address methodological challenges such as cross-sectional dependence, heteroskedasticity, autocorrelation, and slope heterogeneity

The study aims to systematically investigate how urbanization moderates the environmental effects of economic complexity and capital accumulation. It seeks to answer the following key questions: (1) Do the environmental benefits of economic complexity diminish as urban density increases? (2) Does urbanization play a mitigating role in the ecological costs of capital formation? (3) Does the urbanization-environment relationship follow a nonlinear pattern? The findings are expected to offer both theoretical insights and practical implications for sustainable urban policy design

1. Literature review

Urbanization, while offering extensive opportunities in terms of economic growth, infrastructure development, and access to technology, also presents multidimensional challenges to environmental sustainability. Particularly in contexts of rapid and unplanned urban expansion, numerous studies have identified increasing air and water pollution, land degradation, and biodiversity loss as common environmental consequences (McGranahan et al., 2007; Zhang et al., 2022; Voukkali et al., 2024). Recent studies further highlight that rapid urbanization, if not accompanied by adequate green infrastructure planning, can significantly deteriorate environmental quality (Kusiyah et al., 2024). Moreover, fostering urban resilience strategies has been recognized as an essential pathway to mitigate these environmental pressures (Revi et al., 2014), while coordinated urban cluster development offers additional opportunities for enhancing environmental protection (Xu & Luo, 2025). Recent evidence further suggests that spatial expansion and economic intensification within urban areas can produce heterogeneous effects on pollution dynamics, underscoring the multidimensional nature of urban environmental impacts (Wei et al., 2025). In addition, Urbanization-driven transformations are found to significantly alter regional carbon cycles and biogeochemical processes, thereby intensifying global environmental pressures (Shurpali, 2023; Churkina, 2016). However, this relationship is not linear. In advanced economies, urban forms that have reached certain thresholds of institutional capacity and environmental regulation are shown to contribute positively to ecosystem health (Stern, 2017; Cao et al., 2025)

This transformation is largely interpreted through the lens of Ecological Modernization Theory (EMT), which argues that environmental issues are not inevitable byproducts of economic growth but can be addressed through technological innovation, institutional reform, and social learning (Mol & Spaargaren, 2000). Urban areas serve as fertile grounds for this transformation, offering advantages such as high population density, enhanced knowledge exchange, technological diffusion, and economies of scale (Zou et al., 2022; Chang et al., 2024). Additionally, cities often concentrate governance institutions and monitoring mechanisms, making the enforcement of environmental policies more feasible.

Nevertheless, the outcomes envisioned by EMT are not universally achieved. In many low-income or institutionally weak countries, urbanization tends to be characterized by informal settlements, inadequate infrastructure, and fragile governance structures, which amplify environmental pressures rather than alleviate them (Latief et al., 2022; Das et al., 2021; Adebayo & Kirikkaleli, 2022). Thus, the environmental consequences of urbanization are highly contextual, shaped by income levels, governance quality, technological capacity, and spatial planning.

Recent literature suggests that the impact of urbanization on environmental quality may follow an inverted-U trajectory, whereby environmental degradation increases up to a certain threshold of urban development, beyond which environmental indicators begin to improve (Cheng et al., 2023; Liang et al., 2024). This conceptualization, known as the Urban Environmental Kuznets Curve (UEKC), implies that not only the extent but also the quality and form of urbanization determine its environmental implications. For instance, countries with similar urbanization rates may produce divergent environmental outcomes depending on their institutional effectiveness.

Economic complexity, defined as the diversity and knowledge intensity of a country's productive capabilities, has also emerged as a significant determinant of environmental outcomes (Hidalgo & Hausmann, 2009). Complex economies are expected to support sustainable development by producing high value-added goods using cleaner, knowledge-based technologies (Mealy & Teytelboym, 2022). Recent empirical studies increasingly examine how economic complexity and urban dynamics influence environmental outcomes (Bashir et al., 2022; Balsalobre-Lorente et al., 2023; Chang et al., 2024).

Theoretically, more complex economies are assumed to reduce environmental harm due to their capacity for technological innovation, resource efficiency, and alignment with stringent environmental standards (Romero & Gramkow, 2021; Boleti et al., 2021). Indeed, countries that have invested in green technologies, recycling systems, and environmental innovation tend to display a positive association between economic complexity and ecological indicators (Balsalobre-Lorente et al., 2023; Bashir et al., 2022; Pata, 2021).

However, this relationship is not universally consistent. In low- and middle-income countries, increased complexity may coincide with industrial expansion in energy-intensive sectors, thereby exacerbating carbon emissions and resource depletion (Doğan et al., 2019; Aluko et al., 2023; Khezri et al., 2022). The sectoral composition of complexity becomes crucial in this regard. If complexity is driven by environmentally harmful industries, its sustainability benefits may be limited or even reversed (Degirmenci et al., 2024; Adebayo & Kirikkaleli, 2022).

Moreover, the environmental impact of economic complexity is closely tied to a country's energy profile. Economies that combine high complexity with a renewable energy base can limit their ecological footprint, whereas those reliant on fossil fuels may experience diminished sustainability gains (Khezri et al., 2022; Bashir et al., 2022; Balsalobre-Lorente et al., 2023). Therefore, aligning energy transition policies with economic upgrading is essential.

Urbanization, traditionally treated as an independent factor in environmental research, is increasingly recognized as a moderating variable that shapes how structural drivers like economic complexity, capital formation, and energy use translate into environmental outcomes (Mol & Spaargaren, 2000; Zou et al., 2022; Chang et al., 2024). Cities act not only as centers of production and consumption but also as transformative systems that mediate innovation, infrastructure investment, and governance (Balland et al., 2020; Lapatinas et al., 2022; Gomez-Lievano & Patterson-Lomba, 2021). Recent studies further highlight that the internal complexity of urban systems significantly influences environmental trajectories, particularly by shaping resource flows and technological diffusion patterns (Salvati & Carlucci, 2020).

In highly urbanized environments, knowledge-intensive activities are more likely to flourish, thereby amplifying the environmental gains of economic complexity. Yet, without adequate infrastructure or planning, such gains may be eroded by congestion, pollution, and overconsumption of resources (Di Clemente et al., 2021; Fritz & Manduca, 2021). The same holds for capital investments: while green infrastructure in dense cities may yield positive outcomes, uncoordinated capital formation in low-density regions can fragment ecosystems and increase carbon intensity (OECD, 2023; Radoine et al., 2022).

Energy consumption patterns are also shaped by urban form. Centralized heating systems, public transport networks, and clean energy infrastructure can reduce energy intensity in well-planned urban areas (Stern, 2004; Burger et al., 2019). Conversely, urban sprawl and inadequate energy governance may result in high fossil fuel dependency and negative ecological effects (Degirmenci et al., 2024; Wang & Wang, 2024; Kwilinski et al., 2023). Recent empirical evidence highlights that rapid urbanization, when coupled with inefficient energy systems, significantly intensifies environmental degradation by increasing energy intensity and accelerating carbon emissions (Onifade & Alola, 2023; Franco et al., 2017)

Taken together, urbanization operates not only as a direct environmental driver but also as a potential moderator that reshapes the influence of structural factors on environmental outcomes. Although prior studies have examined the environmental impacts of urbanization within broader sustainability frameworks (Chang et al., 2024; Balsalobre-Lorente et al., 2023; Bashir et al., 2022), explicit empirical modeling of urbanization as a moderating variable remains relatively scarce.

In this context, the current study aims to bridge the theoretical and empirical gap by analyzing how urbanization modifies the effects of economic complexity, capital formation, and energy intensity on ecosystem vitality. Using a comprehensive OECD panel dataset spanning 1995–2022, the study applies interaction modeling to assess not only direct relationships but also conditional effects.

The policy implications are manifold. Environmental and development strategies should not focus solely on enhancing technological sophistication or capital accumulation. Instead, they must be embedded within spatial and institutional contexts that enable sustainability. Promoting compact, knowledge-based urbanization, investing in clean infrastructure, and encouraging renewable energy transitions are not only environmental imperatives but also essential components of resilient economic systems.

2. Methodology

2.1 Theoretical Model

The model begins with an extended production function that incorporates economic complexity as a distinct factor of production. Drawing from endogenous growth theory (Mankiw et al., 1992), we express total output (Y) as:

$$Y = A \cdot K^{\alpha} \cdot L^{\beta} \cdot EC^{\gamma} \quad (1)$$

This specification diverges from traditional Cobb-Douglas formulations by explicitly including economic complexity (EC), which captures the knowledge intensity of production. The exponent γ measures how EC augments output independently of capital and labor. Total factor productivity (A) here subsumes not just technology but also institutional factors that vary across urban environments.

Transitioning from production to environmental impacts, the model links economic output to energy demand through a linear dependence:

$$E = \theta \cdot Y \quad (2)$$

Energy consumption (E) scales with output, where φ represents energy intensity. This coefficient varies across economies based on their sectoral composition and technological sophistication – for instance, service-dominated high-EC economies typically exhibit lower φ values than manufacturing-intensive systems (Stern, 2004). The environmental consequences of energy use are then mediated by the pollution intensity of the energy mix:

$$D = \vartheta_0 \cdot (1 - RE)^{\theta} \cdot E \quad (3)$$

Here, D quantifies environmental damage, which depends not just on total energy use but crucially on the renewable energy share (RE). The parameter θ captures diminishing returns to renewables' pollution abatement potential, reflecting real-world constraints in green technology deployment.

Urbanization enters the model through two distinct channels. First, it enhances productivity via agglomeration economies:

$$A = \delta \cdot ln\,(U) \quad (4)$$

The logarithmic form reflects decreasing marginal benefits of urban concentration (Duranton & Puga, 2004), where δ measures how urbanization boosts innovation and resource allocation efficiency. However, beyond an optimal threshold (U_0), negative externalities emerge:

$$A = \delta \cdot ln(U) - (max(0, U - U_0))^2 \quad (5)$$

This quadratic penalty term accounts for congestion costs and infrastructure strains that characterize over-urbanized regions. The ecosystem vitality (EV) then responds to both current and legacy environmental damage:

$$EV_t = \Omega - \lambda \cdot [(1 - \eta) \cdot D_{t-1} + D_t] \quad (6)$$

Where Ω represents the baseline carrying capacity of urban ecosystems, while η quantifies their recovery rate from past damage D_{t-1}. The final specification incorporates urban form's impact:

$$EV_t = \Omega - \lambda \cdot [(1 - \eta) \cdot D_{t-1} + D_t] - \zeta \cdot Spawl \quad (7)$$

The ζ parameter captures how low-density urban expansion (Sprawl) compounds environmental stress through habitat fragmentation and increased energy demand for transportation – a critical consideration for OECD cities facing suburbanization pressures. Following standard urban economics literature, we account for urban sprawl effects through the non-linear term of urbanization (UP^2), which captures the density-reducing nature of uncontrolled expansion.

2.2 Variables and Empirical Model

To examine the hypothesized relationships, we construct a panel dataset using standardized metrics for ecosystem vitality, economic complexity, and urbanization dynamics. The panel dataset covers the period 1995-2022 and includes OECD countries. The selected country group provides diversity in terms of both data reliability and advanced production structure and environmental policies. Table 1 details the variable definitions, measurement approaches, and data sources, which prioritize transparency and reproducibility.

Table 1. Variables, definitions, and sources.

Variables	Abrv.	Indicator	Source
Ecosystem vitality	EV	Ecosystem vitality	YEP
Economic complexity	EC	Economic complexity	HGL
Production	FC	Gross fixed capital formation (constant 2015 US$)	WB
Population	UP	Urban population (% of total population)	WB
Renewable energy	RE	Renewable energy consumption (% of total final energy consumption)	IEA
Energy intensity	EI	Energy intensity	IEA
Interaction term	I_EC	$(EC\ x\ UP)$	AC
Interaction term	I_FC	$(FC\ x\ UP)$	AC

Source: World Bank (2024), World Development Indicators (WB); Yale Center for Environmental Law & Policy (2024), Environmental Performance Index (YEP); Harvard Growth Lab (2024), The Atlas of Economic Complexity (HGL); International Energy Agency (2024), Statistical Review of World Energy (IEA); Author's calculation (AC).

The variable selection in this study is grounded in both ecological economics theory and empirical literature on sustainable development. Ecosystem vitality (EV) serves as the dependent variable, reflecting a nation's capacity to maintain biodiversity, mitigate pollution, and sustainably manage natural resources – a critical metric in OECD countries where urbanization and industrial complexity often strain environmental systems.

Economic complexity (EC), derived from the Hidalgo and Hausmann (2009) framework, captures whether advanced production capabilities correlate with greener technologies or increased resource exploitation. Gross fixed capital formation (FC) controls for the environmental impact of infrastructure investment, as OECD nations balance growth with decarbonization (World Bank, 2024). Urbanization (UP) tests the Environmental Kuznets Curve (EKC) hypothesis, where urban density may initially degrade but later improve ecosystems through economies of scale in green infrastructure (Stern, 2017).

Energy-related variables, renewable consumption (RE) and energy intensity (EI), address the pivotal role of energy transitions in climate policy (IEA, 2024). The interaction terms (EC×UP, FC×UP) examine whether urbanization moderates the ecological effects of economic structure and capital accumulation, a novel contribution to the literature.

Data sources (World Bank, Yale EPI, Harvard Atlas, IEA-Energy Institute) were prioritized for cross-country consistency, with logarithmic transformations applied to non-ratio variables to ensure elasticity interpretations.

The empirical framework begins by specifying the functional relationship between ecosystem vitality (EV) and its determinants, grounded in our theoretical model:

$$EV = f(EC, FC, UP, RE, EI, EC \times UP, FC \times UP) \tag{8}$$

This functional form in Eq.8 captures the direct effects of economic complexity (EC), fixed capital (FC), urbanization (UP), renewable energy (RE), and energy intensity (EI), while explicitly accounting for how urbanization moderates the impacts of EC and FC through interaction terms.

Moving to the estimable econometric specification, we adopt a log-linear form for elasticity interpretation, with urbanization preserved in its original percentage scale due to its bounded nature (0–100%):

$$lnEV_{it} = \beta_0 + \beta_1 lnEC_{it} + \beta_2 lnFC_{it} + \beta_3 UP_{it} + \beta_4 UP_{it}^2 + \beta_5 lnRE_{it} + \beta_6 lnEI_{it} + \beta_7 (lnEC_{it} x UP_{it}) + \beta_8 (lnFC_{it} x UP_{it}) + \epsilon_{it} \tag{9}$$

Here in Eq.9, the quadratic term for urbanization (UP^2) tests for potential nonlinear effects, such as the turning points predicted by ecological modernization theory. The interaction terms (EC×UP and FC×UP) operationalize the hypothesis that urbanization alters the environmental effects of economic production structures.

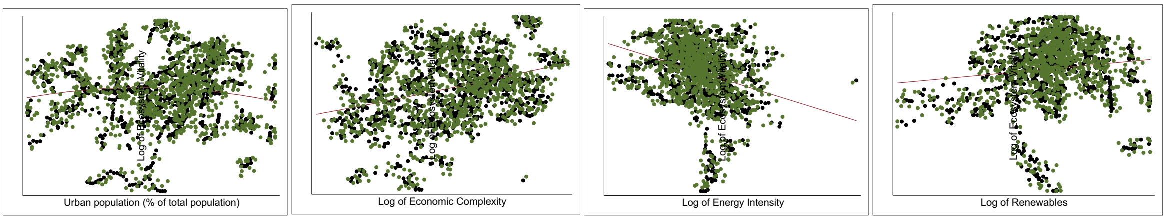
To quantify these conditional relationships, we derive the net (marginal) effects of EC and FC, which vary with urbanization levels:

$$\frac{\partial lnEV_{it}}{\partial lnEC_{it}} = \beta_1 + \beta_7 \cdot LnUP_{it} \tag{10}$$

$$\frac{\partial lnEV_{it}}{\partial lnFC_{it}} = \beta_2 + \beta_8 \cdot LnUP_{it} \tag{11}$$

These partial derivatives expressed in Eq.10 and Eq.11 will be evaluated at critical values of urbanization (minimum, mean, and maximum observed in the sample) to assess how urban contexts reshape EC's and FC's ecological impacts. For instance, a negative β_7 would imply that economic complexity's benefits for ecosystem vitality diminish in highly urbanized settings, while a positive β_8 could signal that urban agglomerations mitigate fixed capital's environmental costs.

Prior to formal estimation, we examine bivariate relationships between ecosystem vitality and core explanatory variables through graphical analysis plotted in Figure 1. These graphical representations provide an initial overview of how fundamental factors such as urbanization, economic complexity, energy intensity, and renewable energy may influence environmental performance.



LnEV-UP LnEV-LnEC LnEV-LnEI LnEV-LnRE

Figure 1. Observed relationships between ecosystem vitality and core explanatory variables.
Source: Own elaboration.

Figure 1(a) displays the bivariate association between urbanization and ecosystem vitality. The scatterplot reflects expected heterogeneity across OECD countries, and the curved fitted line indicates potential nonlinear effects. This visual evidence led us to formally test for quadratic urbanization effects in our econometric specifications. Figure 1(b) presents a positively sloped fitted line between economic complexity (LnEC) and ecosystem vitality. This visual pattern aligns with theoretical expectations that countries with more knowledge-intensive production structures may demonstrate superior environmental performance. The scatterplot in Figure 1(c) visualizes the association between energy intensity (LnEI) and ecosystem vitality. The downward-sloping fitted line preliminarily suggests that higher energy intensity may adversely affect environmental outcomes. Figure 1(d) illustrates the relationship between renewable energy use (LnRE) and ecosystem vitality. The upward-sloping fitted line provides initial evidence that renewable energy consumption may positively influence environmental outputs. The observed patterns in these figures undergo structural testing through formal empirical analyses in the later sections of our research

2.3 Methods

The methodology follows a systematic approach to address the unique challenges of panel data analysis while ensuring robust and reliable results. We begin with diagnostic tests to examine the fundamental properties of our dataset. Preliminary analyses confirm the presence of cross-sectional dependence and slope heterogeneity, rejecting the assumption of homogeneous parameters across countries. Unit root tests reveal mixed stationarity patterns, with some variables requiring first-differencing to achieve stationarity. These findings collectively justify our use of second-generation econometric techniques that explicitly account for these panel data complexities.

The model specification process involves formal testing of fixed versus random effects, with test results strongly favoring fixed effects estimation to control for unobserved country-specific heterogeneity. Additional diagnostic checks identify significant heteroskedasticity, autocorrelation, and cross-sectional dependence in the residuals, while supporting the exogeneity of our regressors. These diagnostic outcomes necessitate specialized estimation techniques that go beyond conventional panel data approaches.

For our core analysis, we implement multiple complementary estimation strategies to ensure robust inference. The primary approach employs panel-corrected standard errors (PCSE) developed by Beck and Katz (1995), to address heteroskedasticity and contemporaneous correlation. To simultaneously handle autocorrelation and cross-sectional dependence, we estimate models with Driscoll and Kraay (1998) standard errors incorporating first-order autoregressive correction (DK-AR1). Recognizing the bounded nature of our ecosystem vitality measures, we supplement these with Poisson pseudo-maximum likelihood estimation featuring high-dimensional fixed effects (PPML-HDFE), following Santos Silva and Tenreyro (2006), which provides consistent estimates under various distributional assumptions. As a final robustness check, we implement feasible generalized least squares (FGLS) estimation to account for panel-specific heteroskedastic patterns (Parks, 1967).

This multi-method strategy serves two critical purposes. First, it allows us to assess whether our findings are robust to different statistical assumptions about error structures and functional forms. Second, it provides a wider framework to examine how urbanization moderates the environmental impacts of economic complexity and fixed capital formation. By systematically addressing the key challenges of panel data analysis - including cross-sectional dependence, heteroskedasticity, autocorrelation, and parameter heterogeneity - we ensure that our results reflect genuine relationships rather than statistical artifacts. In this respect, Figure 2 below depicts empirical methodology design.

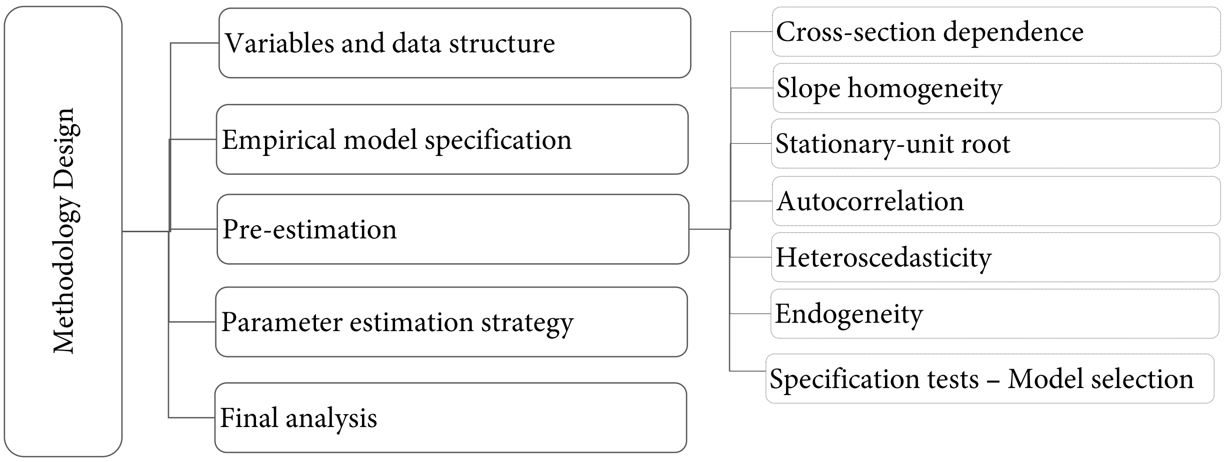


Figure 2. Methodology design.
Source: Own elaboration.

3. Research results

3.1 Descriptive Patterns and Correlations

Before proceeding to econometric analysis, it is critical to assess the distribution and variability of the dataset to ensure the robustness of subsequent estimations. Table 2 presents descriptive statistics for all variables, offering insights into the sample's empirical characteristics and potential outliers that may influence the results.

Table 2. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
EV	1064	50.679	9.727	21.69	70.761
EC	1064	1.646	0.653	0.01	3.047
FC	1064	2.438×10^{11}	5.622×10^{11}	1.443×10^{9}	4.675×10^{12}
UP	1064	76.178	11.105	50.622	98.153
RE	1064	165.813	327.821	0.016	2993.056
EI	1064	1.064	1.80×10^{-9}	1.05×10^{-9}	3.61×10^{-10}

Source: Own elaboration.

The statistics reveal several notable patterns. Ecosystem vitality (EV) exhibits a mean value of 50.68 (SD = 9.73), with a wide range (21.69–70.76), indicating significant cross-country and temporal heterogeneity in environmental performance across OECD nations. Economic complexity (EC) averages 1.65 (SD = 0.65), but its minimum (0.01) and maximum (3.05) values highlight disparities in productive sophistication, possibly reflecting divergent industrialization paths.

For gross fixed capital formation (FC), the substantial standard deviation (5.622×10^{11}) relative to the mean (2.438×10^{11}) suggests skewed investment distributions, likely due to economic size disparities (e.g., smaller vs. larger OECD economies). Urbanization (UP) is uniformly high (mean =

76.18%, SD = 11.11), consistent with OECD's urbanized demographics, though the range (50.62–98.15%) captures variations in urban concentration.

The energy variables show stark contrasts: Renewable energy (RE) has a high SD (327.82) and extreme max value (2,993.06), indicating outliers where certain countries rapidly scaled renewables. Energy intensity (EI)'s near-zero variability (SD = 1.80×10^{-9}) suggests consistent measurement units.

Prior to estimating the multivariate regression model, we examine bivariate correlations between variables to identify potential multicollinearity issues and preliminary patterns in the data. Table 3 presents the correlation matrix for all key variables in the analysis.

Table 3. Matrix of correlations.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) EV	1.000					
(2) EC	0.324	1.000				
(3) FC	0.078	0.287	1.000			
(4) UP	-0.025	0.070	0.149	1.000		
(5) RE	0.012	0.155	0.826	0.150	1.000	
(6) EI	-0.243	-0.285	-0.113	-0.171	-0.044	1.000

Source: Own elaboration.

The correlation matrix reveals several important relationships. Ecosystem vitality (EV) shows a moderate positive correlation with economic complexity (EC) (r = 0.324), suggesting that countries with more sophisticated production structures tend to have better environmental performance. This aligns with ecological modernization theory, where advanced economies may develop technologies that reduce environmental impact. Notably, gross fixed capital formation (FC) demonstrates a strong positive correlation with renewable energy consumption (RE) (r = 0.826), indicating that higher investment levels are associated with greater renewable energy adoption. The negative correlation between energy intensity (EI) and EV (r = -0.243) supports the expected relationship where more energy-efficient economies tend to have higher ecosystem vitality. Similarly, EI's negative correlation with EC (r = -0.285) suggests that economically complex countries tend to use energy more efficiently. Urbanization (UP) shows weak correlations with most variables, with the strongest being a modest positive relationship with FC (r = 0.149). This implies that urban population share alone may not be a strong direct predictor of ecosystem vitality in OECD countries, supporting the inclusion of interaction terms to capture more nuanced relationships.

3.2 Model Diagnostics and Specification Tests

To ensure the reliability of our empirical analysis, we first examine the statistical properties of our dataset. Slope homogeneity was assessed based on the Delta and Swamy S tests proposed by Pesaran and Yamagata (2008), while cross-section independence was examined using CD, CDw, CDw+, and CD* statistics developed by Pesaran (2004, 2015) and Juodis and Reese (2022). Table 4 presents the results of cross-sectional dependence and slope homogeneity tests for OECD countries. The Pesaran (2015)-type CD test (statistic = 9.66, $p < 0.01$) and its power-enhanced version CDw+ (statistic = 1739.20, $p < 0.01$) reveal strong cross-sectional dependence in our panel. This finding suggests the presence of either mutual interactions in environmental policies among countries or their simultaneous exposure to common global shocks. Regarding slope homogeneity, both the Swamy S test ($\chi^2 = 17563.11$, $p < 0.01$) and Delta test ($\Delta = 28.124$, $p < 0.01$) indicate statistically significant parameter heterogeneity across countries.

Table 4. Slope homogeneity and cross-section independence tests.

CD Tests				Homogeneity	
CD	**CDw**	**CDw+**	**CD***	**Delta**	**Swamy S (χ^2)**
9.66*	-1.67***	1739.20*	-0.43	28.124*	17563.11*

Note: * p<0.01, ** p<0.05, *** p<0.10.
Source: Own elaboration.

These results demonstrate that conventional fixed or random effects models might produce misleading inferences. Cross-sectional dependence may substantially underestimate standard errors, creating false significance risks, while unaccounted slope heterogeneity could mask country-specific dynamics crucial for policy recommendations. Therefore, building on these findings, the empirical strategy proceeds by selecting the most appropriate advanced panel methods based on the unit root tests (Table 5) and model selection criteria (Table 6). When the tests show consistent patterns, the analysis prioritizes estimators that simultaneously correct for cross-sectional dependence and accommodate heterogeneous coefficients.

The CDw test results (statistic = -1.67, $p < 0.10$), validated by Juodis and Reese's (2022) simulation studies, provide additional albeit weaker evidence of dependence. These findings align with the hypothesis that coordinated environmental regulations (e.g., Paris Agreement) among OECD nations may strengthen cross-sectional linkages. Our final model selection in Table 8 will explicitly address these statistical properties while maintaining theoretical relevance to ecological institutionalism.

Table 5 presents the results of the panel unit root tests, which explore the time-series characteristics of the variables while accounting for cross-sectional dependence. Following Pesaran (2007), the CADF and CIPS tests were applied to accommodate potential cross-sectional correlations among OECD countries. These results offer a foundation for identifying the stationarity properties of the variables and guiding the appropriate model specification.

Table 5. Pesaran-CIPS and CADF panel unit root test.

Variable	CIPS I(0)	CIPS I(1)	CADF I(0)	CADF I(1)
EV	-2.274	-4.776*	-2.274	-4.776*
EC	-2.557	-4.666*	-2.457	-3.076*
FC	-2.021	-4.163*	-2.389	-3.30*
UP	-1.185	-2.363*	-1.671	-2.147*
RE	-2.854*	.	-2.873**	.
EI	-2.296	-4.901*	-2.063	-3.708*
I_EC	-2.547	-4.671*	-2.448	-3.088*
I_FC	-1.787	-4.093*	-2.134	-3.278*

Note: * $p < 0.01$, ** $p < 0.05$.
Source: Own elaboration.

The unit root test results in Table 5 demonstrate that renewable energy (RE) is the only variable exhibiting stationarity in levels, with both CIPS (-2.854, $p<0.01$) and CADF (-2.873**, $p<0.05$) tests rejecting the unit root hypothesis. All other variables - including ecosystem vitality (EV), economic complexity (EC), fixed capital (FC), urbanization (UP), energy intensity (EI), and both interaction terms (I_EC and I_FC) - show consistent patterns of non-stationarity at levels but achieve stationarity after first differencing, as evidenced by statistically significant results ($p<0.01$) across both test frameworks. These findings indicate that while RE can be analyzed in its level form, the other variables will require appropriate differencing transformations to ensure valid statistical inference in subsequent modeling. The consistent results across both testing approaches lend robustness to these stationarity assessments and provide clear guidance for variable treatment in our empirical analysis.

Before proceeding to estimation, it is essential to determine the appropriate panel data specification that accounts for unobserved heterogeneity. Table 6 presents the results of diagnostic tests for individual and time effects, along with the Hausman test, which collectively guide the choice between fixed, random, or pooled effects models.

Table 6. Specification tests for panel effects and model selection.

	Individual Effect	Time Effect	Mix Effet
LR	$\chi2$=919.47*	$\chi2$=18.85*	$\chi2$=1741.94*
F	F test=122.30*	F test= 13.51*	
LM	$\chi2$= 7811.50*		
Hausman Test $\chi2$ = 53.72*			

Note: * $p < 0.01$.

Source: Own elaboration.

The specification test results in Table 6 provide crucial evidence for determining the appropriate panel data model structure. The highly significant likelihood ratio (LR) statistics for individual effects (χ^2=919.47, p=0.000), time effects (χ^2=18.85, p=0.000), and mixed effects (χ^2=1741.94, p=0.000) collectively reject the null hypothesis of no unobserved heterogeneity, indicating that both country-specific and time-specific factors significantly influence our dependent variable. This conclusion is further supported by the F-test results, which similarly confirm the presence of individual effects (F=122.30, p=0.000) and time effects (F=13.51, p=0.000). The remarkably large Lagrange Multiplier (LM) statistic (χ^2=7811.50, p=0.000) provides additional strong evidence favoring panel data approaches over pooled OLS estimation. Most critically, the Hausman test yields a statistically significant result (χ^2=53.72, p=0.000), decisively rejecting the random effects model in favor of fixed effects specification. These comprehensive test results collectively demonstrate that our empirical analysis requires a fixed effects modeling framework that accounts for both individual country heterogeneity and time-specific variations to produce unbiased and efficient parameter estimates. The overwhelming statistical evidence across all test categories leaves little doubt about the necessity of controlling for unobserved individual and time effects in our panel data analysis.

Before presenting the estimation results, we examine whether our empirical models satisfy key statistical assumptions. Table 7 reports diagnostic tests for heteroskedasticity, autocorrelation, cross-sectional dependence, and endogeneity—potential violations that could bias estimates if unaddressed. These tests validate the robustness of our chosen specifications.

Table 7. Diagnostic tests for model assumptions.

Tests	Hypothesis	Statistics	p-value
Breusch-Pagan / Cook-Weisberg	H_0: Var(u_i) = σ^2	χ2= 63	0.000
White's test	H_0: Var(u_i) = σ^2	χ2= 377	0.000
Wooldridge test	H_0: Cov(u_{it},u_{is}) = 0 $\forall$ t≠s	F = 371	0.000
Breusch-Pagan LM	H_0: Cov(u_{it},u_{jt}) = 0 $\forall$ i≠j	χ2 =5792	0.000
Durbin (score)	H_0: Cov(X_{it},u_{it}) = 0	χ2 = 1.93	0.165
Wu-Hausman	H_0: Cov(X_{it},u_{it}) = 0	F = 1.922	0.166

Source: Own elaboration.

The diagnostic tests in Table 7 reveal several critical insights about our model's properties. First, both the Breusch-Pagan (χ^2=63, p=0.000) and White's tests (χ^2=377, p=0.000) strongly reject the null hypothesis of homoskedasticity, indicating significant heteroskedasticity that necessitates robust standard errors in estimation. Second, the Wooldridge test (F=371, p=0.000) confirms the presence of first-order autocorrelation, further supporting the use of panel-corrected techniques.

The Breusch-Pagan LM test (χ^2=5792, p=0.000) overwhelmingly rejects cross-sectional independence, aligning with our earlier findings of interconnectedness among OECD countries. Crucially, the Durbin (χ^2=1.93, p=0.165) and Wu-Hausman (F=1.922, p=0.166) tests fail to reject the null of exogeneity, suggesting our regressors can be treated as exogenous, a finding that justifies the chosen estimators while precluding the need for instrumental variables.

3.3 Estimation Results

Following the diagnostic results, several methodological adjustments were necessary to ensure the robustness of our empirical approach. To address heteroskedasticity and serial correlation simultaneously, we relied on Driscoll-Kraay standard errors with first-order autoregressive correction (Driscoll & Kraay, 1998). In addition, Panel-Corrected Standard Errors (PCSE) estimation was applied to control for contemporaneous correlation and heteroskedasticity across panels (Beck & Katz, 1995). Feasible Generalized Least Squares (FGLS) estimation was also employed to address panel-specific heteroskedastic patterns and serial correlation, drawing on both classical and contemporary implementations (Parks, 1967; Greene, 2003). Finally, to handle cross-sectional dependence and the semi-continuous nature of the dependent variable, Poisson Pseudo Maximum Likelihood with high-dimensional fixed effects (PPML-HDFE) was implemented (Santos Silva &

Tenreyro, 2006; Correia, Guimarães, & Zylkin, 2020). These methodological adaptations collectively ensure that our empirical strategy remains resilient to the identified violations of classical regression assumptions. The estimation outcomes based on these adjustments are reported in Table 8.

Table 8. Estimations.

Variable	PCSE	DK-AR1	PPML-HDFE	FGLS
LnEC	0.58** (2.52)	0.80* (3.58)	0.78* (8.74)	0.62* (7.68)
LnFC	-0.67* (-2.6)	-0.95* (-4.02)	-0.51* (-13.09)	-0.70* (-14.04)
UP	-0.095* (-2.63)	-0.137* (-4.19)	-0.064* (-12.04)	-0.098* (11.52)
UPS	0.0003** (2.41)	0.0004* (3.98)	0.0002* (9.92)	0.0003* (7.99)
LnRE	0.0270* (3.4)	0.0266* (3.59)	0.0040* (4.73)	0.0232* (16.84)
LnEI	-0.035* (-3.18)	-0.046* (-3.94)	-0.035* (-9.93)	-0.027* (9.66)
I_EC	-0.129** (-2.44)	-0.177* (-3.48)	-0.172* (-8.42)	-0.139* (7.57)
I_FC	0.157* (2.65)	0.221* (4.06)	0.116* (13.08)	0.162* (13.9)
cons	8.21* (3.89)	10.62* (5.43)	4.71* (15.66)	8.77* (20.58)

Note: * p<0.01, ** p<0.05, (z-statistics).
Source: Own elaboration.

The estimation results presented in Table 8 demonstrate remarkable consistency across four distinct methodologies, reinforcing the robustness of our findings. Beginning with economic complexity (LnEC), all models show statistically significant positive effects, with coefficients ranging from 0.58 (PCSE) to 0.80 (DK-AR1), suggesting that advanced economic structures consistently contribute to improved environmental outcomes. The negative coefficients for fixed capital formation (LnFC), ranging from -0.51 (PPML-HDFE) to -0.95 (DK-AR1), indicate that traditional investment patterns may exert persistent environmental pressures across OECD nations.

Urbanization (UP) displays uniformly negative and significant coefficients (-0.064 to -0.137), supporting the hypothesis that urban expansion initially strains ecosystems, while its squared term (UPS) reveals a consistent positive turning point (0.0002 to 0.0004), corroborating the Environmental Kuznets Curve hypothesis for urbanization effects. Renewable energy (LnRE) maintains positive significance across all specifications (0.0040 to 0.0270), though the magnitude varies considerably, with FGLS showing the strongest effect (0.0232) and PPML-HDFE the most conservative (0.0040).

Energy intensity (LnEI) exhibits expected negative coefficients (-0.027 to -0.046), confirming that energy efficiency improvements consistently benefit ecosystem vitality. The interaction terms reveal nuanced insights: I_EC's negative coefficients (-0.129 to -0.177) suggest that economic complexity's environmental benefits diminish in highly urbanized contexts, while I_FC's positive coefficients (0.116 to 0.221) imply urbanization mitigates fixed capital's negative environmental impacts.

Notably, the PPML-HDFE estimates generally show larger absolute z-statistics, reflecting the method's efficiency in handling our data's characteristics. The consistency of significance levels ($p<0.01$, $p<0.05$) across methods, despite their different handling of heteroskedasticity, autocorrelation, and cross-sectional dependence, strongly validates our core findings. The constant terms' variation (4.71 to 10.62) appropriately captures method-specific baseline differences while maintaining the relative stability of other coefficients.

This analysis confirms that our key results are not artifacts of specific methodological choices, but represent robust relationships observable across diverse estimation frameworks. The convergence of findings from PCSE (addressing heteroskedasticity), DK-AR1 (handling autocorrelation), PPML-HDFE (managing cross-sectional dependence), and FGLS (optimizing efficiency) provides particularly strong evidence for our hypothesized relationships. The minor variations in coefficient magnitudes offer valuable insights into how different data challenges affect parameter estimation, with all methods ultimately supporting the same substantive conclusions about the urbanization-environment nexus in OECD countries.

3.4 Interaction Terms and Urban Moderation

To fully capture how urbanization moderates the environmental impacts of economic complexity and fixed capital, Table 9 presents the net (marginal) effects calculated across minimum, mean, and maximum urban population levels. These results, derived from four robust estimation methods, reveal the conditional nature of the relationships identified in our main specifications, offering nuanced policy insights.

Table 9. Net effects of economic complexity and fixed capital on ecosystem vitality across urbanization levels.

Net effect	PCSE	DK-AR1	PPML-HDFE	FGLS
LnEC @ UPmin (0.506)	0.51	0.71	0.69	0.55
LnEC @ UPmean (0.762)	0.48	0.67	0.65	0.51
LnEC @ UPmax (0.982)	0.45	0.63	0.61	0.48
LnFC @ UPmin (0.506)	-0.59	-0.84	-0.45	-0.62
LnFC @ UPmean (0.762)	-0.55	-0.78	-0.42	-0.58
LnFC @ UPmax (0.982)	-0.52	-0.73	-0.40	-0.54

Notes: UP (urban population) scaled to 0-1 range. Net effects for LnEC calculated as $\beta_1 + \beta_7 \cdot LnUP_{it}$, for LnFC as $\beta_2 + \beta_8 \cdot LnUP_{it}$, and evaluated at UP ∈ {UP_{min}, UP_{mean}, UP_{max}} to assess urban moderation effects.
Source: Own elaboration.

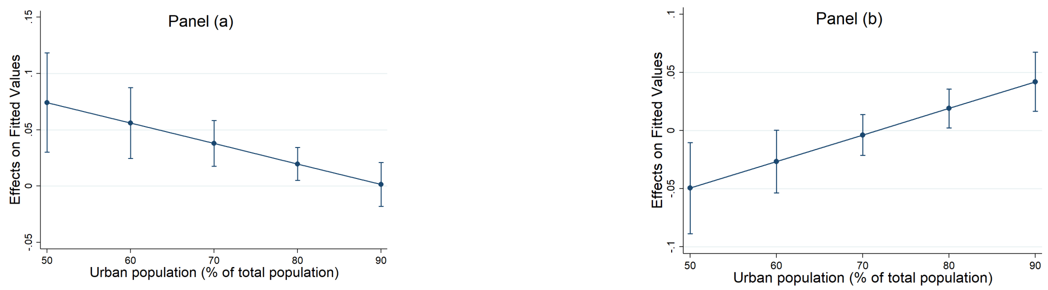
The net effects presented in Table 9 reveal patterns about how urbanization moderates the environmental impacts of economic complexity and fixed capital. For economic complexity (LnEC), we observe a consistent but diminishing positive effect across urbanization levels. The PCSE estimates, for instance, show that a one-unit increase in LnEC improves ecosystem vitality by 0.51 units at minimum urbanization (UP=0.506), declining to 0.48 units at mean urbanization (UP=0.762), and further to 0.45 units at maximum urbanization (UP=0.982). This gradual attenuation suggests that while knowledge-intensive production structures benefit ecosystems, their marginal utility weakens in highly urbanized contexts, possibly due to saturation of technological spillovers or intensified resource competition in dense urban areas. A similar pattern emerges across all four estimation methods, with the DK-AR1 model showing slightly stronger effects and PPML-HDFE yielding more conservative estimates, reflecting methodological differences in handling panel data challenges.

For fixed capital (LnFC), the net negative effects persist but exhibit meaningful moderation with urbanization. The DK-AR1 results illustrate this trend most clearly: at minimum urbanization, a one-unit increase in LnFC reduces ecosystem vitality by 0.84 units, while at maximum urbanization, this penalty softens to 0.73 units. This pattern implies that urban environments may partially counteract the ecological costs of physical capital accumulation through agglomeration benefits, more efficient infrastructure utilization, or stricter urban environmental regulations. The consistency of this moderating effect across PCSE, FGLS, and PPML-HDFE specifications - despite their distinct approaches to addressing heteroskedasticity and dependence - strengthens confidence in this finding.

The comparative stability of these net effects across estimation methods is particularly noteworthy. While coefficient magnitudes vary predictably (with PPML-HDFE typically producing smaller absolute values due to its exponential mean specification), all models agree on both the direction of effects and their urbanization-contingent nature. This robustness underscores that our core findings about urban moderation are not artifacts of specific methodological choices, but reflect fundamental relationships in the data. The results collectively suggest that urban planners and policymakers should consider place-specific strategies: promoting economic complexity may yield greater environmental dividends in less urbanized regions, whereas mitigating fixed capital's ecological impact could prove most effective in highly urbanized areas through targeted investments in green infrastructure and circular economy practices.

3.5 Marginal Effects Visualization

To further explore the role of urbanization in conditioning the environmental effects of structural economic variables, we present marginal effect plots in Figure 3. These visualizations illustrate how the impact of economic complexity (LnEC) and fixed capital formation (LnFC) on ecosystem vitality (EV) varies across different levels of urban population.



$\beta_1 + \beta_7 \cdot UP_{it}$ @ $UP \in \{50,60,70,80,90\}$ $\quad$ $\beta_2 + \beta_8 \cdot UP_{it}$ @ $UP \in \{50,60,70,80,90\}$

Figure 3. Urbanization as a Moderator of the Effects of Economic Complexity and Fixed Capital on Ecosystem Vitality.
Source: Own elaboration.

Fig. 3(a) reveals that the marginal effect of economic complexity declines steadily as urbanization increases. At lower urban population levels (e.g., 50%), economic complexity yields a significantly positive contribution to ecosystem vitality. However, as the urban population approaches 90%, this effect becomes statistically indistinct. These results are consistent with the net effect estimates reported in Table 9, which show a gradual attenuation of ECI's environmental benefits across increasing urbanization levels. This finding supports the hypothesis that while knowledge-intensive production structures promote environmental improvements, their marginal utility may decline in densely urbanized contexts due to resource saturation, congestion, or diminishing technological returns.

Fig. 3(b), in contrast, demonstrates a reverse moderation pattern. The marginal effect of fixed capital formation increases with urbanization, turning from negative at lower urbanization rates to positive and statistically significant at higher levels. This suggests that urban environments enhance the environmental efficiency of capital investments—possibly due to better infrastructure integration, agglomeration effects, and stronger environmental regulations in densely populated regions. Again, the graphical insights align closely with the coefficient trends in Table 9, where the environmental cost of fixed capital decreases across urbanization tiers.

Fig. 3 corroborates our main hypothesis that urbanization not only exerts a direct influence on environmental quality but also reshapes the environmental implications of key structural drivers. The consistency of these patterns across four estimation techniques, PCSE, DK-AR1, PPML-HDFE, and FGLS, confirms the robustness of our findings and underscores the significance of spatial context in environmental-economic modeling.

4. Discussion

The findings of this study yield several critical insights into the environmental implications of economic structure and urbanization. First, the diminishing marginal benefits of economic complexity in highly urbanized contexts resonate with the saturation hypothesis advanced by Fritz and Manduca (2021), who argue that knowledge spillovers and innovation gains may plateau once urban systems reach a certain density threshold. This observation reinforces the idea that technological sophistication alone is insufficient to generate sustained ecological improvements without concurrent institutional and spatial transformations.

Second, the moderating role of urbanization in attenuating the environmental costs of capital formation aligns with evidence from Chang et al. (2024), which underscores how agglomeration economies in urban environments can enhance the efficiency of infrastructure deployment and resource allocation. This suggests that well-planned urban growth may buffer the traditionally negative ecological effects of capital accumulation.

Furthermore, the identification of an inverted-U relationship between urbanization and environmental performance provides empirical support for the Urban Environmental Kuznets Curve (UEKC) hypothesis (Cheng et al., 2023). This pattern implies that environmental degradation may initially rise with urban expansion but improve once cities surpass critical thresholds in regulatory capacity, institutional quality, and clean technologies.

Collectively, these findings substantiate core tenets of Ecological Modernization Theory (Mol & Spaargaren, 2000), especially the notion that structural reform and innovation, when embedded in spatially adaptive frameworks, can yield ecological dividends. Importantly, this study extends prior research by modeling urbanization not merely as an independent driver but as a moderating structure that shapes the effects of economic inputs on ecosystem vitality.

From a policy standpoint, the results advocate for a more nuanced approach to sustainability in high-income contexts. Policymakers should focus not only on promoting technological advancement and capital investment but also on strengthening urban institutions, enhancing spatial planning, and fostering region-specific environmental governance models that integrate urban density, complexity-driven innovation, and infrastructural efficiency.

Conclusions

This study, based on panel data from 38 OECD countries over the period 1995–2022, demonstrates that urbanization significantly moderates how economic complexity and capital formation influence environmental outcomes. Rather than serving as a passive backdrop, urban contexts actively condition both the direction and magnitude of these structural impacts on ecosystem vitality.

Three key findings emerge. First, the positive environmental contributions of economic complexity weaken as urban density increases. This attenuation likely reflects challenges such as congestion, resource competition, and diminishing returns to innovation in highly urbanized settings. Second, urbanization appears to mitigate the ecological costs associated with capital accumulation, likely through more efficient infrastructure use, shared systems, and stronger regulatory oversight. Third, the analysis confirms a nonlinear (inverted U-shaped) relationship between urbanization and environmental performance, consistent with the Urban Environmental Kuznets Curve hypothesis. Environmental degradation initially intensifies during early stages of urban growth but tends to improve once cities reach more advanced levels of development, likely due to enhanced governance capacities and greater diffusion of green technologies. This finding underscores the importance of urban governance capacity and integrated planning in achieving environmental sustainability, as emphasized by global frameworks (UN-Habitat, 2022).

The findings concerning energy dynamics reveal additional nuances. While renewable energy adoption consistently improves environmental quality, persistently high energy intensity continues to pose significant challenges. This suggests that while transitioning to renewable energy is essential, complementary strategies, such as implementing energy efficiency standards and promoting circular economy practices, are also critical for reducing overall energy demand and achieving deeper environmental gains.

From a policy perspective, these insights underscore the importance of spatially differentiated approaches. Efforts to promote economic complexity could be more effective when tailored to peri-urban or moderately dense areas, whereas capital investment strategies may benefit from focusing on compact, resource-efficient urban forms. Rather than viewing urbanization as uniformly beneficial or detrimental, policymakers are encouraged to recognize its contingent effects and design sustainability strategies that are sensitive to local urban contexts.

Theoretically, this study contributes to the ecological modernization literature by reframing urbanization as a moderating mechanism rather than an independent driver of environmental change. It also reinforces the Urban Environmental Kuznets Curve (UEKC) hypothesis by showing that sustainability outcomes hinge not only on affluence, but also on institutional maturity and technological absorption. Practically, the findings highlight the need for differentiated sustainability strategies that align with urban form, economic complexity, and capital dynamics.

Nonetheless, several limitations should be acknowledged. First, this study relies on country-level panel data, which may obscure important intra-national differences in urban structure and environmental governance. Second, while the analysis incorporates key structural and energy-related variables, it does not account for potentially influential institutional or cultural factors. Third, the exclusive focus on OECD countries may limit the generalizability of the findings to non-OECD or developing contexts.

Future research could further explore whether these moderating dynamics vary across (1) different regional groupings, (2) stages of economic development, or (3) urban governance models. Additionally, city-level analyses could offer more granular insights into how intra-urban variations shape the links between economic structure, urbanization, and environmental outcomes. City-level evidence further supports the dynamic relationship between urban growth and air quality (Zhu, 2025), highlighting the relevance of localized analyses in urban environmental studies. By conceptualizing urbanization as an active moderating force, this study offers a more sophisticated interpretation of how economic and ecological systems interact during sustainability transitions.

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