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Exploring the Deep Roots of the Environmental Kuznets Curve (Ekc): Evidence from a Global Sample

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Abstract

Our paper adopts a deep-roots approach to examining the Environmental Kuznets Curve (EKC) by tracing its origins beyond industrialization and into the dawn of human civilization. We hypothesize that the roots of environmental degradation lie not only in modern-day markets or technology, but in the evolutionary arc of societies themselves. Using a two-stage empirical framework applied to a sample of 130 countries, we show that early transitions into agriculture, technology adoption, and human settlement patterns shaped modern growth trajectories, which in turn influence environmental degradation in line with EKC dynamics. Our findings imply that climate change is not merely a policy failure but also a civilizational inheritance, and sustainable futures cannot be engineered solely through contemporary interventions. Therefore, climate policy must evolve from reactive governance to deep-time reengineering to realign humanity's path with the planet's limits, not just for today, but for millennia ahead.

Keywords: Environmental Kuznets Curve (EKC); state history; agricultural transition; early technology adoption; early settlement; environmental degradation



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1. Introduction

To understand the relationship between economic development and environmental degradation or sustainability, economists have proposed the Environmental Kuznets Curve (EKC) as a conceptual framework linking human activity to ecosystem dynamics (Grossman & Krueger, 1995; Beckerman, 1992; Andreoni & Levinson, 2001; Dinda, 2005). The EKC suggests that humans, which are the most influential biotic agents in the ecosystem, engage in economic activity through the production of goods and services for survival. However, these activities deplete the planet's natural resources, reduce biodiversity, and disrupt ecosystems, ultimately affecting abiotic factors such as temperature and humidity, which weakens the Earth's capacity to support life (Kelly, 1992). While earlier schools of thought viewed industrialization and environmental degradation as inseparable, the EKC hypothesizes that economic growth can occur without environmental harm, provided it is driven by clean technologies and robust pollution control mechanisms (Phiri et al., 2024).

To date, the EKC remains one of the most researched topics in environmental economics, with most scholars conceptualizing it as a post-industrial phenomenon (Dasgupta et al., 2002; Dinda, 2004; Stern, 1998, 2004, 2017; Wang et al., 2024). However, an emerging group of unconventional growth economists argue that post-industrial growth trajectories are rooted in institutional and technological legacies established long before modern civilization (Galor & Weil, 2000; Galor & Moav, 2002; Galor, 2007, 2011, 2024). This raises

a fundamental question: can the origins of environmental degradation be traced back to millennia before industrialization?

Our study takes a novel approach by applying a deep-root framework to the EKC. Specifically, we conduct a two-stage empirical investigation into the historical drivers of environmental degradation. In the first stage, we use deep-rooted variables to predict patterns of modern economic growth. We hypothesize that societies with longer histories of governance structures (Bockstette et al., 2002; Putterman, 2008; Putterman & Weil, 2010; Borcan et al., 2018), earlier transitions into the Neolithic era (Hibbs & Olsson, 2004; Putterman, 2008), early human settlements (Ahlerup & Olsson, 2012), and prehistoric technological adoption (Comin et al., 2010) are more likely to achieve sustained economic growth. In the second stage, we examine how these historically shaped growth paths influence current levels of environmental degradation, hypothesizing an inverted U-shaped relationship consistent with EKC dynamics.

Our study makes a novel contribution by exploring whether the origins of the EKC can be traced back to the earliest phases of human civilization, and to the best of our knowledge, we are the first study to do so. While previous work (e.g., Lindmark, 2002; Churchill et al., 2018) has analyzed the EKC in pre-industrial contexts using centuries-long time series, our study goes further back, to the Neolithic transition, and adopts a cross-sectional two-stage least squares (2SLS) approach. By leveraging deep-root variables that reflect multiple dimensions of early human development, we aim to identify the evolutionary channels that underpin modern patterns of growth and emissions. In doing so, we bridge two bodies of literature: the deep roots of development and EKC research.

Our work significantly extends the EKC framework by modeling climate change from an evolutionary perspective. This is particularly relevant given that contemporary climate solutions, such as carbon taxes and climate financing, focus on nudging economies toward the ‘technological segment’ of the EKC, where growth coexists with reduced emissions (Stiglitz, 2019). Yet, the persistent failure to halt climate change suggests that deeper, long-term drivers may be at play. Identifying these could help craft more durable strategies for sustainable growth.

Our findings reveal that early agricultural transitions, early technologies, and early settlement patterns are strong predictors of modern economic growth and consequently of carbon emissions, thus following the traditional hump-shaped EKC. These dynamics hold across both industrialized and developing economies, though the turning points occur earlier in the latter. Our results remain robust even when using ecological footprint as an alternative measure of environmental degradation.

The main implication of our study is that climate change is not merely a result of market inefficiencies or technological shortfalls but is an inherited outcome of civilization itself. Policymakers must therefore recognize environmental degradation not just as a modern policy issue but as a product of deep historical pathways. Solutions must be multi-generational, historically informed, and grounded in a long-view understanding of humanity’s evolving relationship with nature. The future of climate policy lies not only in regulating present-day emissions, but also in reengineering the legacies that have shaped the human–environment nexus across millennia.

Against this backdrop, the remainder of the paper is organized as follows. The next section presents a review of the relevant literature. Section 3 outlines the empirical framework and data. Section 4 discusses the findings, and Section 5 concludes the paper.

2. Literature Review

Our study relates to two strands of literature. Firstly, it relates to the Environmental Kuznets Curve (EKC), introduced by Grossman and Krueger (1995) as an environmental

interpretation of [Kuznets \(1955\)](#) inverted U-shaped relationship between income and inequality. Theoretically, the EKC is framed as a two-stage development process: (i) in the early stages of economic growth, environmental degradation increases due to heavy reliance on pollution-intensive industries and dirty energy sources (scale effects); (ii) after reaching a certain income threshold, economies begin to adopt cleaner technologies and industries, allowing for continued growth with declining environmental damage (technical effects). [Dinda \(2005\)](#) formalized these dynamics in an endogenous growth model where capital is divided between production—generating pollution—and abatement activities aimed at environmental clean-up. The hump-shaped EKC emerges as capital allocation shifts from production to abatement with economic development.

Empirically, many studies have tested the EKC by regressing environmental degradation on GDP, its square, and various control variables. Highly cited seminal works by [Selden and Song \(1994\)](#), [Shafik \(1994\)](#), [Holtz-Eakin and Selden \(1995\)](#), [Cole et al. \(1997\)](#), [Taskin and Zaim \(2000\)](#), [Apergis and Payne \(2009\)](#), [Arouri et al. \(2012\)](#), [Apergis and Ozturk \(2015\)](#), [Bilgili et al. \(2016\)](#), and [Wang et al. \(2023\)](#) support the existence of an inverted U-shaped relationship between economic growth and carbon emissions. In contrast, influential studies such as [Agras and Chapman \(1999\)](#), [Harbaugh et al. \(2002\)](#), [Perman and Stern \(2003\)](#), [Azomahou et al. \(2006\)](#) and [Jaunky \(2011\)](#) fail to confirm this pattern. Other popular studies, including [Galeotti et al. \(2006\)](#), [Narayan and Narayan \(2010\)](#), [Narayan et al. \(2016\)](#), [Özokcu and Özdemir \(2017\)](#), and [Li et al. \(2022\)](#), find that the EKC relationship is more evident in advanced economies than in developing countries. As summarized in several review and bibliometric studies, the empirical support for the EKC remains mixed, highlighting the need for further investigation ([Stern, 1998, 2004, 2017](#); [Dasgupta et al., 2002](#); [Dinda, 2004, 2005](#); [Sarkodie & Strezov, 2019](#); [Bashir et al., 2021](#); [Koondhar et al., 2021](#); [Anwar et al., 2022](#); [Leal & Marques, 2022](#); [Naveed et al., 2022](#); [Ajmi et al., 2023](#); [Vásquez Coronado et al., 2024](#); [Lau et al., 2025](#)).

Secondly, our study engages with the deep roots literature, which posits that modern economic outcomes are shaped by historical foundations that predate industrialization. [Galor and Weil \(2000\)](#) and [Galor and Moav \(2002\)](#) pioneered the unified growth theory, which explains how human societies transitioned from Malthusian stagnation to modern growth. According to this view, humanity's struggle for survival led to the emergence of foundational institutions—such as agriculture, early state formation, and basic technologies—that spurred innovation and population growth, ultimately creating the vast global disparities in income and development observed today ([Galor, 2007, 2011, 2024](#)).

Empirical research in this domain has developed various deep-root indicators to assess how ancient factors influence modern economic trajectories. [Bockstette et al. \(2002\)](#), [Putterman \(2008\)](#), [Putterman and Weil \(2010\)](#), and [Borcan et al. \(2018\)](#) constructed an index of state history, capturing a country's exposure to formal governance structures from 1 CE to 1500 CE. This measure considers the presence of supra-tribal polities, the nature of internal versus external rule, and the territorial reach of early states. [Hibbs and Olsson \(2004\)](#) and [Putterman \(2008\)](#) introduced a metric for agricultural transition, indicating the number of years since a society shifted from foraging to farming. [Ahlerup and Olsson \(2012\)](#) developed a duration of settlement index, estimating uninterrupted human habitation for 191 countries by synthesizing genetic, archaeological, and climatological evidence—from early human dispersal out of East Africa to island settlements like the Seychelles in 1756. [Comin et al. \(2010\)](#) created an index of early technology adoption, measuring the presence of key technologies across domains such as agriculture, transport, military, industry, and communication as of 2000 AD, with an emphasis on usage rather than intensity.

As discussed in the introduction, our study bridges these two literatures by exploring whether deep-rooted historical factors influence the shape and dynamics of the modern

EKC across a cross-sectional sample of countries. To our knowledge, this is the first study to examine how ancient institutional, agricultural, settlement, and technological histories shape environmental degradation through their effect on modern economic growth. We employ a two-stage empirical strategy: in the first stage, we assess the impact of deep-root variables on current economic development; in the second, we evaluate the effect of development on carbon emissions via the EKC framework. The empirical methodology is detailed in the next section.

3. Model Specification and Data

3.1. Model Specification

To examine the relationship between deep-rooted historical variables and environmental degradation, this study applies a two-stage least squares (2SLS) estimation method. In the first stage, deep-root variables are used as instrumental variables (IVs), while GDP per capita (GDPPC) is treated as the endogenous variable. The estimated cross-sectional regression takes the form:

$$\text{GDP}_i = \alpha + \beta \text{deep_root} + \beta_X \text{CONTROLS} + \text{error} \quad (1)$$

This first stage captures the effect of long-term historical and institutional characteristics on present-day economic development. We expect a positive relationship between the deep-root proxies and economic growth, i.e., $\beta > 0$. Note that we estimated four of these regressions using different measures of the deep root variable, i.e., state history, agricultural transition, early technology, and time since original settlement.

In the second stage, the predicted values of GDP per capita from the first stage (GDPPC_HAT) are used to estimate their impact on environmental degradation. Specifically, carbon emissions (CO_2) are regressed on these predicted income values and their squared terms as follows:

$$\text{CO}_2_i = \alpha + \beta_1 \text{GDPPC_HAT} + \beta_2 \text{GDPPC_HAT}^2 + \beta_X \text{CONTROLS} + \text{error} \quad (2)$$

The inclusion of the squared term allows us to test for a non-linear relationship consistent with the Environmental Kuznets Curve (EKC). Under the EKC hypothesis, we expect β_1 to be positive and β_2 to be negative (i.e., $\beta_1 > 0$, $\beta_2 < 0$), indicating an inverted U-shaped curve where emissions first rise with income and then decline after a certain threshold. The turning point of the EKC is computed by taking the derivative of the second-stage equation with respect to GDPPC_HAT and setting it to zero, which yields:

$$X^* = -\beta_1 / (2\beta_2) \quad (3)$$

3.2. Empirical Data

The data used in the analysis fall into four main categories. The first set comprises the dependent variables: GDP per capita for the year 2020 and carbon dioxide emissions (measured in kilotons), both sourced from the World Bank Development Indicators. As a robustness check, ecological footprint data, obtained from the Global Footprint Network, are used as an alternative measure of environmental degradation.

The second category includes the deep-root variables used as instruments in the first-stage regression. These include the state history index, which captures the duration and strength of formal statehood from 1 CE to 1500 CE and is sourced from [Putterman and Weil \(2010\)](#); the Neolithic transition variable, measuring years since the shift from foraging to agriculture, also from [Putterman and Weil \(2010\)](#); the original settlement variable, which records the uninterrupted human habitation in a region based on archaeological and genetic

evidence and is provided by [Ahlerup and Olsson \(2012\)](#); and the early technology adoption index, which reflects historical use of technologies in agriculture, military, transport, and communication, sourced from [Comin et al. \(2010\)](#).

The third group consists of control variables included in both stages of the estimation. These include a democracy index measuring the extent of democratic governance, and an ecological diversity index (Ecopol), both taken from [Arbatli et al. \(2020\)](#). Additional controls include a binary indicator for whether a country is landlocked, obtained from the CIA World Factbook, and dummy variables for former colonies of Britain, France, and Portugal, based on classifications by [Ziltener et al. \(2017\)](#).

Descriptive statistics for all variables used in the study are presented in Table 1, while Appendix A (Table A1) lists the 130 countries, both industrialized and developing, comprising the cross-sectional sample and Appendix B (Table A2) lists the countries by colonial origin.

Table 1. Descriptive statistics of the variables.

	Mean	Standard Deviation	Jarque-Bera	J-B (Prob.)	Minimum	Maximum
<i>Outcome variables</i>						
GDPPC 2020	8.61	1.38	4.72	0.09	5.57	11.56
CO ₂ 2020	9.51	2.50	0.80	0.67	1.89	16.21
EF 2020	16.64	2.04	51.91	0.00	7.23	22.36
<i>Deep-rooted variables</i>						
State history	0.95	0.75	99.03	0.00	0.04	3.86
Agricultural transition	4.71	2.43	6.48	0.04	0.24	10.50
Early technology	0.45	0.20	19.86	0.00	0.17	1.01
Origtime	10.57	1.05	9.69	0.01	7.09	11.98
<i>Controls and dummies</i>						
Democratic	0.41	0.38	13.35	0.00	0.00	1.00
EcoPol	0.67	0.19	131.41	0.00	0.02	0.93
Landlocked	0.22	0.41	54.90	0.00	0.00	1.00
Britain	0.38	0.49	30.08	0.00	0.00	1.00
France	0.18	0.39	87.05	0.00	0.00	1.00
Portugal	0.06	0.23	1667.31	0.00	0.00	1.00

4. Empirical Results

4.1. Main Regression Results

We begin our empirical investigation by presenting the results from the baseline two-stage least squares (2SLS) estimations. The first-stage regression results are reported in Table 2, while the second-stage results are shown in Table 3. Each table comprises four models, corresponding to different specifications based on the use of the four different deep-rooted variables in the estimation process.

From the first-stage regressions, we find that the state history variable produces a statistically insignificant coefficient, indicating that it is not a robust predictor of modern economic growth within our sample of countries. This result corroborates earlier findings by [Murphy and Nowrasteh \(2018\)](#) and [Fani and Phiri \(2024\)](#), who similarly concluded that state history does not significantly influence current economic performance. In contrast, the other three deep-rooted variables—agricultural transition, early technological adoption, and the timing of early human settlement—are all positively and significantly associated with GDP per capita. These findings align with the historical development literature, including the works of [Hibbs and Olsson \(2004\)](#), [Putterman \(2008\)](#), [Ahlerup and Olsson \(2012\)](#), and

Comin et al. (2010), who have demonstrated that early institutional, technological, and demographic transitions exert long-term impacts on economic development.

Turning to the second-stage results reported in Table 3, we observe that the predicted values of GDP per capita (GDP_HAT) and its squared term (GDP_HAT²) both yield coefficients with the expected signs: GDP_HAT is positive and significant, while GDP_HAT² is negative and significant. This pattern confirms the existence of an inverted U-shaped Environmental Kuznets Curve (EKC), whereby environmental degradation initially rises with economic growth but eventually declines after a certain income threshold. These results are consistent with prior empirical findings on the EKC in international contexts, as documented in the literature by Selden and Song (1994), Shafik (1994), Holtz-Eakin and Selden (1995), Taskin and Zaim (2000), Apergis and Payne (2009), Apergis and Ozturk (2015), Bilgili et al. (2016), and Wang et al. (2023).

The estimated coefficients on the control variables produce mixed results across both stages. In the first-stage regressions, we find that democracy and ecological polarization tend to have a positive and significant relationship with economic growth, suggesting that democratic institutions and ecologically varied environments may support developmental outcomes. Furthermore, former British colonies are observed to perform better economically relative to countries previously colonized by other powers, possibly due to the institutional advantages inherited from British governance structures, as noted in Phiri (2021). In the second-stage regressions, most control variables are statistically insignificant, indicating limited explanatory power in terms of environmental outcomes. However, ecological diversity consistently exerts a significant and beneficial influence on environmental degradation, highlighting the potential role of natural environmental heterogeneity in mitigating ecological harm.

Table 2. First stage estimation results.

	Dependent Variable: LnGDPPC			
	(1) State History	(2) Agricultural Transition	(3) Early Technology	(4) Origtime
<i>Independent variables</i>				
Deep_root	−0.12 (0.70)	0.59 (0.00) ***	9.19 (0.00) ***	0.84 (0.00) ***
<i>Controls and dummies</i>				
Democratic	2.41 (0.00) ***	2.22 (0.00) ***	−1.58 (0.03) *	2.45 (0.00) ***
EcoPol	9.88 (0.00) ***	5.57 (0.00) ***	6.52 (0.00) ***	−1.47 (0.07) *
Landlocked	0.13 (0.80)	0.22 (0.60)	0.42 (0.38)	−0.44 (0.14)
Britan	1.54 (0.00) ***	1.75 (0.00) ***	1.17 (0.01) ***	−0.30 (0.31)
France	0.47 (0.45)	1.05 (0.04) **	0.02 (0.97)	−0.79 (0.03) **
Portugal	−0.13 (0.90)	1.37 (0.09) *	0.73 (0.40)	0.16 (0.78)
No. of observations	130	140	123	130

Notes: *, ** and *** indicate significance at 10%, 5% and 1% significance levels, respectively. *p*-values reported in ().

Table 3. Second stage estimation results.

Dependent Variable: CO ₂ Emissions				
	(1) State History	(2) Agricultural Transition	(3) Early Technology	(4) Origtime
<i>Independent variables</i>				
GDPPC_HAT	8.06 (0.00) ***	2.42 (0.00) ***	2.42 (0.00) ***	2.84 (0.00) ***
GDPPC_HAT ²	−0.19 (0.00) ***	−0.12 (0.00) ***	−0.12 (0.00) ***	−0.19 (0.00) ***
<i>Controls and dummies</i>				
Democratic	−10.78 (0.11)	0.50 (0.44)	1.00 (0.17)	−10.78 (0.11)
EcoPol	−52.71 (0.05) *	−2.06 (0.09) *	−2.97 (0.04) *	−52.71 (0.05) *
Landlocked	−0.97 (0.12)	−0.91 (0.05) *	−0.48 (0.35)	−0.97 (0.12)
Britan	−6.00 (0.14)	0.58 (0.21)	0.73 (0.16)	−6.00 (0.14)
France	−2.65 (0.05) *	−0.73 (0.19)	−0.42 (0.48)	−2.65 (0.05) *
Portugal	0.00 (1.00)	−0.95 (0.27)	−0.36 (0.70)	0.00 (1.00)
Turning point	21.21	10.08	10.08	7.47
No. of observations	129	138	122	129

Notes: *, ** and *** indicate significance at 10%, 5% and 1% significance levels, respectively. *p*-values reported in ().

4.2. Sensitivity Analysis: Developed Versus Non-Industrialized Countries

In the first set of sensitivity analyses, we partition the dataset into two sub-samples comprising developed and non-industrialized countries. This distinction is essential because existing literature suggests that the dynamics of the Environmental Kuznets Curve (EKC) vary between advanced and developing or emerging economies (Galeotti et al., 2006; Narayan & Narayan, 2010; Özokcu & Özdemir, 2017; Li et al., 2022). The regression results for these groups are reported in Tables 4 and 5. To streamline the presentation, we focus on the coefficients of the deep-root variables in the first-stage regressions and the predicted GDP per capita values (GDP_HAT) in the second-stage regressions.

The results indicate that early agricultural transition, early technological adoption, and the timing of original human settlements (Origtime) are all positively and significantly associated with modern economic growth in both sub-samples, consistent with the patterns identified in the full-sample analysis. In contrast, the state history variable remains statistically insignificant across most model specifications, reinforcing earlier findings about its limited predictive relevance. In the second-stage estimates, the GDP_HAT and GDP_HAT² variables retain their expected signs: the linear term is positive and significant, while the squared term is negative and significant. This confirms the robustness of the inverted U-shaped EKC relationship in both developed and non-industrialized countries.

However, a notable difference emerges in the estimated EKC turning points. Developed countries exhibit considerably higher turning points than their non-industrialized counterparts, implying that the latter group can potentially begin reducing environmental degradation at lower income levels. This observation suggests that less developed countries

do not necessarily need to attain the same income thresholds as industrialized nations before transitioning into the declining phase of the EKC. These findings highlight the importance of tailoring climate and economic strategies to a country's specific developmental stage, rather than applying uniform policy frameworks across diverse economic contexts.

Table 4. Estimates for industrialized countries.

<i>Panel A: Deep roots of economic growth</i>	Stage 1 Dependent variable: LnGDPPC (2020)			
	(1) State history	(2) Agricultural transition	(3) Early technology	(4) Origtime
Independent variable				
Historic variable	0.37 (0.60)	0.66 (0.00) ***	12.63 (0.00) ***	1.05 (0.00) ***
Controls & dummies	✓	✓	✓	✓
Observations	40	44	40	40
	Stage 2 Dependent variable: CO ₂ emissions (2020)			
	(1) State history	(2) Agricultural transition	(3) Early technology	(4) Origtime
Independent variable				
GDPPC_HAT	2.02 (0.11)	1.88 (0.00) ***	1.77 (0.00) ***	1.76 (0.00) ***
GDPPC_HAT ²	−0.11 (0.00) ***	−0.08 (0.00) ***	−0.08 (0.00) ***	−0.08 (0.08) *
Controls & dummies	✓	✓	✓	✓
Turning points	N/A	11.75	11.06	11.00
Observations	39	43	40	39

Note: *, ** and *** indicate significance at 10%, 5% and 1% significance levels, respectively. *p*-values reported in ().

Table 5. Estimates for non-industrialized countries.

	Stage 1 Dependent variable: LnGDPPC (2020)			
	(1) State history	(2) Agricultural transition	(3) Early technology	(4) Origtime
Independent variable				
Historic variable	−0.01 (0.98)	0.51 (0.00) ***	7.24 (0.00) ***	0.77 (0.00) ***
Controls & dummies	✓	✓	✓	✓
Observations	90	96	83	90
	Stage 2 Dependent variable: CO ₂ emissions (2020)			
	(1) State history	(2) Agricultural transition	(3) Early technology	(4) Origtime
Independent variable				
GDPPC_HAT	11.01 (0.12)	0.65 (0.00) ***	0.70 (0.00) ***	0.68 (0.00) ***
GDPPC_HAT ²	−0.05 (0.00) ***	−0.04 (0.00) ***	−0.04 (0.00) ***	−0.05 (0.00) ***
Controls & dummies	✓	✓	✓	✓
Turning points	N/A	8.13	8.75	6.80
Observations	90	95	82	90

Note: *, ** and *** indicate significance at 10%, 5% and 1% significance levels, respectively. *p*-values reported in ().

4.3. Sensitivity Analysis: Alternative Measure of Environmental Degradation

In our second sensitivity analysis, we utilize ecological footprint (EF) as an alternative measure of environmental degradation within the EKC framework. EF is considered a more comprehensive metric than carbon emissions, as it captures the environmental impacts of both production and consumption activities, whereas carbon emissions largely reflect pollution stemming from production alone (Bilgili & Ulucak, 2018; Hassan et al., 2019; Phiri & Tembo, 2023). The two-stage least squares (2SLS) estimation results using EF are presented in Tables 6–8, corresponding to the full sample, industrialized economies, and developing countries, respectively.

The findings are broadly consistent across all three samples. Specifically, all deep-rooted variables—except for state history—exhibit positive and statistically significant relationships with economic growth, which subsequently contributes to environmental degradation. These results further affirm the importance of deep-rooted historical and institutional factors in shaping contemporary economic trajectories and their associated environmental outcomes. Additionally, the estimated turning points of the EKC remain substantially lower in developing countries compared to their industrialized counterparts. This suggests that developing economies may experience the environmental benefits of economic maturation at earlier stages of growth. Overall, these outcomes closely align with those obtained from the earlier analysis based on carbon emissions, leading us to conclude that our core findings are robust to the choice of environmental degradation indicator and remain consistent across different country groupings.

Table 6. 2SLS Estimates deep root EF-EKC for full sample.

Stage 1				
Dependent variable: LnGDPPC (2020)				
	(1) State history	(2) Agricultural transition	(3) Early technology	(4) Origtime
Independent variable				
Historic variable	−0.12 (0.70)	0.59 (0.00) ***	9.19 (0.00) ***	0.84 (0.00) ***
Controls & dummies	✓	✓	✓	✓
Observations	130	140	123	130
Stage 2				
Dependent variable: Ecological footprint (2020)				
	(1) State history	(2) Agricultural transition	(3) Early technology	(4) Origtime
Independent variable				
GDPPC_HAT	7.29 (0.02) **	4.04 (0.00) ***	4.11 (0.00) ***	4.34 (0.00) ***
GDPPC_HAT ²	−0.29 (0.00) ***	−0.21 (0.00) ***	−0.21 (0.00) ***	−0.27 (0.00) ***
Controls & dummies	✓	✓	✓	✓
Turning points	12.57	9.62	9.79	8.04
Observations	129	138	122	129

Note: *, ** and *** indicate significance at 10%, 5% and 1% significance levels, respectively. *p*-values reported in ().

Table 7. 2SLS Estimates deep root EF-EKC for developed countries.

Stage 1				
Dependent variable: LnGDPPC (2020)				
	(1)	(2)	(3)	(4)
	State history	Agricultural transition	Early technology	Origtime
Independent variable				
Historic variable	0.37 (0.60)	0.66 (0.00) ***	12.63 (0.00) ***	1.05 (0.00) ***
Controls & dummies	✓	✓	✓	✓
Observations	40	44	40	40
Stage 2				
Dependent variable: Ecological footprint (2020)				
	(1)	(2)	(3)	(4)
	State history	Agricultural transition	Early technology	Origtime
Independent variable				
GDPPC_HAT	3.80 (0.01) ***	3.34 (0.00) ***	3.42 (0.00) ***	2.98 (0.00) ***
GDPPC_HAT ²	−0.18 (0.00) ***	−0.14 (0.00) ***	−0.17 (0.00) ***	−0.13 (0.00) ***
Controls & dummies	✓	✓	✓	✓
Turning points	10.56	11.93	10.06	11.46
Observations	39	42	39	39

Note: *, ** and *** indicate significance at 10%, 5% and 1% significance levels, respectively. *p*-values reported in ().

Table 8. 2SLS Estimates deep root EF-EKC for developing countries.

Stage 1				
Dependent variable: LnGDPPC (2020)				
	(1)	(2)	(3)	(4)
	State history	Agricultural transition	Early technology	Origtime
Independent variable				
Historic variable	−0.01 (0.98)	0.51 (0.00) ***	7.24 (0.00) ***	0.77 (0.00) ***
Controls & dummies	✓	✓	✓	✓
Observations	90	96	83	90
Stage 2				
Dependent variable: Ecological footprint (2020)				
	(1)	(2)	(3)	(4)
	State history	Agricultural transition	Early technology	Origtime
Independent variable				
GDPPC_HAT	4.37 (0.52)	0.78 (0.00) ***	0.83 (0.00) ***	0.77 (0.00) ***
GDPPC_HAT ²	−0.06 (0.00) ***	−0.05 (0.00) ***	−0.05 (0.00) ***	−0.05 (0.00) ***
Controls & dummies	✓	✓	✓	✓
Turning points	90	96	83	90
Observations	N/A	7.80	8.30	7.70

Note: *, ** and *** indicate significance at 10%, 5% and 1% significance levels, respectively. *p*-values reported in ().

5. Conclusions and Policy Implications

Our study investigated the deep historical origins of environmental degradation by embedding the Environmental Kuznets Curve (EKC) within an evolutionary development framework. Using a cross-sectional two-stage least squares (2SLS) approach, we linked four deep-rooted factors (i.e., early agricultural transition, prehistoric technological adop-

tion, early human settlement, and ancient governance structures) to modern patterns of economic growth and environmental harm. Our findings reveal that, with the exception of state history, all deep roots significantly predict contemporary income levels, which in turn drive pollution along an inverted U-shaped EKC path. These patterns persist across industrialized and developing countries and remain robust when replacing carbon emissions with ecological footprint, indicating that the environmental consequences of development are not merely a recent phenomenon but they are the long shadow of civilization itself.

These results have important policy implications. The agricultural transition, which is often celebrated as the dawn of civilization, emerges as the first human act of large-scale environmental reconfiguration. Societies that adopted agriculture earlier have had more time to exploit ecological systems and emit. Thus, climate policy must expand beyond present-day emissions to account for ‘ecological debt’ accumulated across millennia. Carbon pricing, reparative climate financing, and differentiated global targets must reflect not only current output but also ancestral land use patterns that shaped our planetary inheritance.

Our findings on prehistoric technological adoption indicate that technology is not an external fix to environmental decline—it is its original cause and carrier. If early innovations laid the path to today’s emissions, then we must ensure that future technologies do the opposite. Climate policy must become pre-emptive, not reactive: investing in green innovation must be seen as a moral imperative, especially in equipping developing nations with sustainable tech pathways. Technology must be designed not only for efficiency but for ecological empathy, embedding sustainability into the very architecture of innovation.

Finally, the geography of early human settlement and the legacy of governance structures offer critical lessons. Where and how humans first organized their communities determines today’s urban sprawl, infrastructure intensity, and institutional capacity to manage environmental crises. Countries with long histories of governance bear a special burden: their robust institutions must now be reoriented toward climate leadership. Meanwhile, those with later development trajectories should be seen not as laggards but as stewards of ecological futures. In short, addressing climate change demands more than emissions cuts—it requires a historical reckoning with the civilizational roots of growth, and policy frameworks which reengineer the future from the past.

In practice, policy implementation must also adapt to an era of heightened uncertainty marked by geopolitical conflict, climate volatility, pandemic shocks, and fluctuating monetary conditions. Flexible climate frameworks are essential. This includes adaptive carbon pricing mechanisms that adjust to macroeconomic instability, resilient supply chains for green technologies, and emergency governance protocols for climate-related disruptions. Historical responsibility must therefore be integrated not only into long-term targets but also into short-run stabilization strategies that remain effective under crisis conditions.

Whilst our analysis focused on the standard quadratic EKC, future work could extend this by introducing a cubic term. A cubic EKC would allow us to test for more complex income–emissions dynamics, such as, whether very-high-income countries experience a second rise in pollution or a flattening out of environmental gains. This is an important step, as our current specification cannot capture such patterns.

Also, since climate policy is increasingly shaped by uncertainty ranging from geopolitical tensions to pandemics and financial shocks, future work should examine how these sources of instability interact with long-run historical forces. Doing so would bring the EKC framework closer to the policy environment in which real-world climate decisions are now made.

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Appendix A. List of Countries

Table A1. List of industrialized and developing countries.

Industrialized Countries				Developing Countries				
Antigua & Barbuda	Guyana	Portugal	Afghanistan	Cameroon Central African Republic	Gabon	Lebanon	Niger	Tajikistan
Australia	Hungary	Qatar	Albania	Chad	Gambia	Lesotho Libya	Nigeria	Tanzania
Austria	Iceland	Romania	Algeria	China	Georgia	Madagascar	Pakistan	Thailand
Bahrain	Ireland	Russia	Angola	Colombia	Ghana	Malawi	North Macedonia	Togo
Barbados	Israel	San Marino	Argentina	Comoros	Grenada	Malaysia	Papua New Guinea	Tonga
Belgium	Italy	Saudi Arabia	Armenia	DRC	Guatemala	Maldives	Senegal	Tunisia
Brunei	Japan	Seychelles	Azerbaijan	Rep. of Congo	Guinea-Bissau	Mali	Serbia	Paraguay
Bulgaria	Kuwait	Singapore	Bahamas	Costa Rica	Haiti	Marshall Islands	Sierra Leone	Peru Samoa
Canada	Latvia	Slovakia	Bangladesh	Dominica	Mauritania	Mauritius	Solomon Islands	São Tomé & Príncipe
Chile	Lithuania	Slovenia	Belarus	Dominican Republic	Honduras	Mexico	Somalia	Philippines
Croatia	Luxembourg	Spain	Belize	Ecuador	India	Fed. Micronesia	South Africa	Rwanda
Cyprus	Malta	Sweden	Benin	El Salvador	Indonesia	Moldova	Sri Lanka	Turkey
Czech Republic	Nauru	Switzerland	Bhutan		Iran			Turkmenistan
	Netherlands	Trinidad and Tobago			Iraq	Mongolia	Saint Lucia	Tuvalu
	New Zealand							
Denmark	Norway	United Arab Emirates	Bolivia	Eritrea	Jamaica	Morocco	St Vincent & the Grenadines	Uganda
Estonia	Oman	United Kingdoms	Bos. & Herzegovina	Eswatini	Jordan	Mozambique	Sudan	Ukraine
Finland	Palau	United States	Botswana	Ethiopia	Kazakhstan	Myanmar	Suriname	Uzbekistan
France	Panama	Uruguay	Brazil	Fiji	Kenya	Namibia	Syria	Vanuatu
Germany	Poland		Burundi		Kiribati	Nepal		Venezuela
Greece			Burkina Faso		Kyrgyzstan	Nicaragua		Vietnam
			Cape Verde		Laos			Zambia
			Cambodia					Zimbabwe

Note: the main regressions include the full sample (all countries).

Appendix B. Former Colonies by Colonial Origin

Table A2. List of countries by colonial origin.

Former Colony *	Britain	France	Portugal	Former Colony *	Britain	France	Portugal	Former Colony *	Britain	France	Portugal
Algeria	No	Yes	No	Guinea-Bissau	No	No	Yes	Paraguay	Yes	No	No
Angola	No	No	Yes	Guyana	Yes	No	No	Romania	Yes	No	No
Ant. & Barbuda	Yes	No	No	Haiti	No	Yes	No	Saint Lucia	Yes	No	No
Australia	Yes	No	No	India	Yes	No	No	San Marino	Yes	No	No
Bahamas	Yes	No	No	Iraq	Yes	No	No	Senegal	Yes	Yes	No
Bahrain	Yes	No	No	Israel	Yes	No	No	Serbia	No	No	No
Bangladesh	Yes	No	No	Jamaica	Yes	No	No	Seychelles	Yes	Yes	No
Barbados	Yes	No	No	Jordan	Yes	No	No	Sierra Leone	Yes	No	No
Belize	Yes	No	No	Kenya	Yes	No	No	Singapore	Yes	No	No
Benin	No	Yes	No	Kiribati	Yes	No	No	Solomon Islands	Yes	No	No
Bhutan	Yes	No	No	Kuwait	Yes	No	No	Somalia	Yes	No	No
Botswana	Yes	No	No	Laos	No	Yes	No	South Africa	Yes	No	No
Brazil	No	No	Yes	Lebanon	No	Yes	No	Sri Lanka	Yes	No	Yes
Brunei	Yes	No	No	Lesotho	Yes	No	No	St Vin. & the Gren.	Yes	Yes	No
Burkina Faso	No	Yes	No	Libya	Yes	No	No	Sudan	Yes	No	No
Cambodia	Yes	Yes	No	Madagascar	No	Yes	No	Suriname	Yes	No	No
Cameroon	Yes	Yes	No	Malawi	Yes	No	No	Syria	No	Yes	No
Canada	No	Yes	No	Malaysia	Yes	No	Yes	Tajikistan	Yes	No	No
Cape Verde	No	Yes	No	Maldives	Yes	No	No	Tanzania	No	Yes	No
Central Afr. Rep.	No	Yes	No	Mali	No	Yes	No	Thailand	No	No	Yes
Colombia	No	Yes	No	Malta	No	No	No	Togo	Yes	No	No
Comoros	No	Yes	No	Marshall Islands	Yes	No	No	Tonga	Yes	No	No
Costa Rica	No	Yes	No	Mauritania	No	Yes	No	Trinida & Tobago	No	Yes	No
Denmark	Yes	Yes	No	Mauritius	Yes	Yes	No	Turkmenistan	Yes	No	No
Ecuador	Yes	No	No	Mozambique	No	Yes	No	Tuvalu	Yes	No	No
El Salvador	Yes	No	Yes	Myanmar	No	No	Yes	Ukraine	Yes	No	No
Eritrea	Yes	No	No	Namibia	Yes	No	No	United Kingdoms	Yes	No	No
Eswatini	Yes	No	No	Nauru	Yes	No	No	United States	No	No	Yes
Fiji	Yes	No	No	Nepal	Yes	No	No	Uzbekistan	Yes	Yes	No
Gabon	No	Yes	No	Nicaragua	Yes	No	No	Venezuela	No	Yes	No
Gambia	Yes	No	No	Nigeria	No	Yes	No	Vietnam	Yes	No	No
Ghana	Yes	No	Yes	North Macedonia	Yes	No	No	Zambia	Yes	No	No
Grenada	Yes	Yes	No	Norway	No	Yes	No	Zimbabwe	Yes	No	No
Guinea	No	Yes	No	Palau	Yes	No	No				

* Former colony refers to countries previously colonized by the respective colonial powers based on [Ziltener et al. \(2017\)](#).

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