Asymmetric Impact of Country Size, Cleaner Energy, and Human Capital on Ecological Footprint: A Mediating Effect

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Abstract: This study evaluates the impact of country size, cleaner energy, human capital on ecological footprint in the case of G5 (Developing) and G7 (Developed) economies from 1996 – 2020. We use CSD-capturing regressions and MM-QRG for baseline and robust analysis to validate empirically. The analysis depicts that country size promotes ecological footprint in G5 and G7 economies across quantiles that may have a negative impact to the environment. On the other hand, human capital investment, technological innovation and market capitalization in G7 economies are not supportive than G5 economies across quantiles. It shows that developing economies are more concern about futuristic-environmental policies to support SDGs and energy transitions path. Therefore, the policy makers should consider country size, cleaner energy capacity, human capital importance, and innovation-driven step while formulating policies on ecological footprint for G5 and G7 economies.

Keywords: Ecological footprint; Cleaner Energy; Human capital; CSD-capturing Regression; MM-QREG.

JEL Codes: Q57; Q42; J24; C23; C21

1. Introduction

The interplay between economic growth, technological innovation, and environmental sustainability is a critical junction shaping national development trajectories. Nations strive to balance economic expansion with environmental standards. The G7 economies (Canada, France, Germany, Italy, Japan, the UK, and the US), recognized for their advanced economies, technological capacities, and strong regulatory frameworks, face the challenge of developing sustainable models that minimize ecological footprints without undermining economic viability. In contrast, G5 nations (Mexico, India, China, Brazil, and South Africa), marked by rapidly growing economies, confront unique challenges and opportunities. Sustainable development in these countries requires adopting cleaner technologies, overcoming infrastructural and regulatory constraints, and mitigating the environmental consequences of industrialization and urbanization (Lian, 2024). Both sets of economies grapple with rising pollution due to natural resource demand, posing threats to health and economic stability (Yilanci & Pata, 2020). Escalating non-recyclable waste, resource depletion, carbon emissions, and climate change highlight the need for national environmental policies and sustainable development initiatives (Lee et al., 2022).

Historically, greenhouse gas emissions were the primary measure of environmental degradation. Rees (1992) and Wackernagel and Rees (1996) proposed the ecological footprint as a comprehensive metric quantifying a population's demand on nature (Yilanci & Pata, 2020). High ecological footprint scores indicate increased pollution and declining environmental quality (Yu et al., 2024). For industrialized nations, sustainable economic progress requires preserving natural resources. Thus, examining ecological footprint dynamics in G7 and G5 countries is crucial to understanding global industrial environmental impacts.

Globalization, when effectively managed, can yield positive environmental outcomes (Wang et al., 2023). Key determinants of ecological footprint include financial development, cleaner energy use, technological progress, economic expansion, urbanization, and industrialization (Lian, 2024). Emerging nations must accelerate economic growth while minimizing ecological impacts (Jahanger et al., 2022). Endogenous growth theory suggests that R&D-driven technological innovation enhances the efficiency of resource and energy use (Churchill et al., 2019), potentially yielding long-term environmental improvements (Sherif et al., 2022). Innovation fosters sustainable technology adoption, improves capital and labor productivity, and enables access to clean energy, positioning R&D investments as critical for reducing ecological footprints.

However, the impact of R&D varies by context. Zhang et al. (2022) found that in some emerging economies (Russia, Mexico, Brazil, China, and India), a 1% increase in R&D expenditures can increase ecological footprint by 0.075–0.082%, illustrating the environmental risks of unregulated industrial growth. Similarly, economic expansion often exacerbates environmental degradation in developing nations. Beyond technological and economic factors, human capital—derived from education—affects environmental outcomes. Education enhances awareness of climate change and fosters pro-environmental behavior, including adoption of renewable energy (Chankrajang & Muttarak, 2017). Improved human capital strengthens the understanding of environmental consequences, encouraging sustainable resource use.

Economic growth also influences renewable energy adoption. As countries reach higher income levels, environmental awareness rises, prompting governments and firms to prioritize renewable energy sources, supporting growth trajectories that mitigate ecological harm (Destek & Sinha, 2020). Despite this, the role of stock market development in environmental outcomes remains underexplored. Stock market evolution can influence ecological footprints through investment patterns, technological adoption, resource allocation, and regulatory frameworks (Younis et al., 2021; Zeqiraj et al., 2020). Its effects are context-dependent, influenced by market size, efficiency, volatility, and integration (Topcu et al., 2020). Asiedu (2024) finds that higher stock market capitalization in emerging economies reduces ecological footprints, highlighting the potential of financial development in sustainable transitions.

This study investigates the effects of country size, clean energy, and human capital on ecological footprint, with technological innovation, R&D, and market capitalization as mediating factors. It covers G5 (developing) and G7 (developed) economies from 1996 to 2020. G7 nations exhibit high urbanization (75.6% on average), trade volumes, and skilled labor, yet all but Canada show ecological deficits—consuming more resources than their ecosystems regenerate (GFN, 2024). G5 economies are rapidly urbanizing and industrializing, with all but Brazil facing ecological deficits. India has notably expanded renewable energy, generating ~40% of its energy from renewables in the past decade and targeting sustainability by 2030. China, while a major contributor to environmental degradation, has also implemented renewable energy policies to meet Paris Agreement commitments, though challenges remain in limiting warming below 2°C (Wu et al., 2023).

Comparative analysis reveals divergent patterns in environmental impacts between G7 and G5 economies. Using CSD-capturing regressions and MM-QRG for baseline and robust analysis, results indicate that in G5 economies, country size and market capitalization reduce ecological footprint, while cleaner energy, human capital, technological innovation, and R&D increase it. In G7 economies, effects diverge, with country size, cleaner energy, human capital, and market capitalization influencing ecological footprint differently. Robust quantile analysis shows country size promotes ecological footprint in both G5 and G7 nations, while human capital, technological innovation, and market capitalization exhibit stronger environmental relevance in developing economies. These findings suggest that G5 nations are more proactive in integrating future-oriented environmental policies to support sustainable development goals and energy transition paths.

2. Past studies

2.1. Ecological footprint in G5 and G7 Economies

The ecological footprint (EF) measures the environmental impact of human activities, including infrastructure development, forest and crop resource utilization, marine use, livestock grazing, and carbon emissions (Ozcan et al., 2018; Ahmed et al., 2020a; Danish et al., 2020). It serves as a comprehensive indicator to assess how human actions affect natural ecosystems. Traditional energy sources—coal, oil, and gas—are major drivers of global pollution, particularly in emerging economies, raising concerns about long-term growth (Tugcu et al., 2012). Nations rich in natural resources can mitigate environmental degradation by reducing fossil fuel consumption and managing imports (Balsalobre-Lorente et al., 2018). Sustainable resource management and efficient supply-demand strategies help slow resource depletion, allowing ecosystems to recover (Merino-Saum et al., 2018). Human activities such as agriculture, mining, and deforestation exacerbate environmental degradation, and over the past 50 years, humanity's ecological footprint has grown by roughly 190%, with over 80% of the global population living under poor environmental conditions (Sarkodie, 2020; GFN, 2024).

G7 economies face challenges of declining biocapacity, high urbanization, and large ecological footprints (Ahmad et al., 2020b; Ahmad et al., 2021; Balsalobre-Lorente et al., 2024; Nathaniel, 2021). Accounting for 46% of global GDP while consuming 23% of global energy, five G7 members—UK, France, Germany, Japan, and the US—rank among the top ten globally for ecological footprint (Bildirici & Gökmenoğlu, 2017; Xia & Liu, 2024). In 2019, per capita EF ranged from 3.9 gha (UK) to 7.9 gha (Canada), well above the global average of 2.77 gha, with the G7 average at 5.35 gha (GFN, 2024). Except for Canada, all G7 nations are in ecological deficit, consuming more resources than their ecosystems can regenerate (Ahmad et al., 2020b). Nevertheless, investments in high-tech industries and cleaner energy have helped reduce ecological footprints, highlighting the importance of innovation and environmental regulation (Lian, 2024). G7 countries are characterized by high economic complexity, which can increase ecological footprint (Rafique et al., 2022; Ikram et al., 2021; Huang et al., 2022). However, Balsalobre-Lorente et al. (2024) show an inverted U-shaped relationship: beyond a threshold, advanced innovation, renewable energy adoption, and human development contribute to long-term EF reduction. Conversely, urbanization and economic growth increase ecological footprint in G7 nations, whereas financial globalization and technological innovation help mitigate it (Ahmad et al., 2021). Substantial investments in clean energy and technology have further reduced environmental impacts through efficiency improvements and greater public awareness, whereas developing nations respond more slowly due to technological and economic limitations (Lian, 2024). In emerging economies, technological innovation has limited influence on EF, while globalization reduces it, and economic growth continues to elevate it (Yang et al., 2021; Pata et al., 2024).

Emerging economies also significantly contribute to environmental degradation through resource overexploitation and pollution from industrial and solid waste. Among G5 nations, Brazil's EF is 2.6 gha per capita, near the global average, while China faces a deficit of 3.51 gha, India 1 gha, Mexico 2.5 gha, and South Africa 3.4 gha (GFN, 2024). Notably, China, India, and Brazil rank among the top five countries with the highest ecological footprints (Bashir et al., 2024). China's rapid economic growth and urbanization have made it the world's largest energy consumer and leading environmental polluter (Xin et al., 2023). Despite progress in eco-friendly infrastructure and environmental policies, EF across its 28 provinces has risen by an average of 40.26%, with some northwestern provinces exceeding 100%, emphasizing the urgent need for sustainable resource management (Xin et al., 2024). Nevertheless, China's green energy investments and policy measures demonstrate a commitment to environmental sustainability, with technical innovation mitigating some ecological impacts (Raihan, 2023; Feng et al., 2024; Du et al., 2024; Ahmad et al., 2023).

India faces similar challenges, with high dependence on energy-intensive industries causing significant environmental degradation. By 2018–19, it had the highest EF among carbon-emitting nations and ranked among the top ten in carbon emissions (Villanthenkodath et al., 2024). Over the past 45 years, China's per capita EF increased faster than GDP growth, while India showed a modest decline, reflecting differing environmental trajectories (Galli et al., 2012). Bashir et al. (2024) demonstrate that technological advancement and geothermal energy can reduce EF over time in countries with high ecological pressures, including China, the USA, India, Brazil, and Japan. Energy consumption and globalization exhibit nonlinear effects on EF in BIRCS nations. Sun et al. (2024) show that in China and India, energy use increases EF across most quantiles, while in South Africa, it reduces EF in most cases. Globalization raises EF at higher quantiles in China and South Africa but decreases it in Brazil, India, and Russia. In Mexico, economic growth and resource extraction amplify EF, with high energy intensity further contributing to ecological deficits (Hossain et al., 2022).

2.2. Cleaner energy and Ecological footprint

The relationship between renewable energy use and the ecological footprint (EF) is central to sustainable development and environmental preservation. Rising fossil fuel consumption and environmental degradation have spurred research on how renewable energy affects ecological outcomes, generally highlighting its positive impact (Javed et al., 2023; Raghutla et al., 2022; Sohag et al., 2024). Lian (2024) confirms that investments in renewable energy and advanced technology sectors substantially reduce EF in G7 countries. Emerging economies, including Brazil, China, India, and Mexico, have also shown gradual improvements in ecological sustainability, although their impact remains limited compared to G7 nations due to less advanced renewable energy infrastructure (Dogan & Korkut Pata, 2022). Renewable energy development optimizes energy structures and facilitates transitions to sustainable systems (Bozatli & Akca, 2023). Using the AMG method, studies indicate that renewable energy consumption significantly reduces EF and environmental pressure in OECD countries (Li et al., 2023; Sadiq et al., 2023). Similarly, Hasan et al. (2024) find that increased renewable energy use in major oil-consuming nations lowers CO2 emissions and EF, emphasizing its environmental benefits.

However, in some developing contexts, the effects of renewable energy are less pronounced. Nathaniel et al. (2024) report that in certain developing countries, green energy has no significant impact on EF, while globalization and financial development reduce EF by 0.25% and 0.08%, respectively. Raghutla et al. (2022) observe significant EF reductions from renewable energy use in N-11 countries (1990–2018), whereas Usman and Hammar (2021) find that renewable energy and financial development slightly increase EF in APEC countries (0.4274% and 0.0927%). These findings suggest that the ecological benefits of renewable energy depend heavily on its integration into the broader energy mix and supporting policies (Meo et al., 2023; Liu et al., 2022).

3. Research Gap

A review of existing literature reveals that numerous studies have explored the impact of renewable energy, human capital, technological innovation, and economic growth on reducing the ecological footprint in G7 and E7 economies (Lian, 2024; Huang et al., 2022). Several of these investigations have focused specifically on either developed or emerging economies (Ahmad et al., 2020b; Nathaniel, 2021; Balsalobre-

Lorente et al., 2024; Zhang et al., 2022; Xia & Liu, 2024; Sun et al., 2023). However, there remains a notable lack of empirical evidence addressing the combined influence of country size, human capital, and clean energy on the ecological footprint when considered alongside technological innovation, R&D, and market capitalization—particularly in the context of G7 and G5 economies. This study addresses that gap by analyzing the asymmetric relationships among these key variables using CSD-adjusted regression models and MM-QRG for both baseline and robustness checks, leveraging the most recent data available. Moreover, the study offers a comparative perspective on G7 and G5 countries, highlighting their unique approaches and impacts as advanced and emerging economies in managing ecological footprints.

4. Data and Methods

4.1. Data description and sources

This study employs a panel dataset to examine factors influencing ecological sustainability, with the Ecological Footprint (EF) as the main dependent variable. EF, measured in global hectares, represents the biologically productive area required to meet a population's consumption demands, including cropland, grazing land, forest land, fishing grounds, built-up areas, and the capacity to absorb carbon emissions. Data are sourced from the Global Footprint Network. Economic development is captured by GDP per capita (Y) in constant 2015 US dollars, used to test the Environmental Kuznets Curve (EKC) hypothesis, which suggests that higher income initially increases EF but later reduces it as cleaner technologies are adopted (World Bank, WDI). Research and Development (R&D) expenditure (RD), expressed as a percentage of GDP, reflects national innovation efforts, expected to reduce ecological degradation through cleaner production and efficient resource use. Technological innovation (TI) is proxied by the sum of resident and non-resident patent applications, indicating technological progress, which may either alleviate or exacerbate environmental pressures depending on the nature of innovations (WIPO; World Bank). Renewable energy consumption (CE), expressed as a percentage of total final energy, captures the transition toward sustainable energy, expected to mitigate EF (World Bank; IEA). Market capitalization (MC), the total value of listed companies as a percentage of GDP, reflects financial market depth and its role in supporting green investments (World Bank; national stock exchanges). The Financial Development Index (FD1), constructed by the IMF and scaled 0–1, measures financial system depth, access, and efficiency, facilitating environmentally oriented investment.

Human capital (HC1), sourced from the Penn World Table 10.01, is based on average years of schooling and returns to education, promoting environmental awareness and adoption of sustainable practices. For empirical analysis, the study specifies a production function linking EF with digital finance, GDP, R&D, and industry value added, capturing the combined influence of economic, technological, financial, and human development factors on green innovation and ecological sustainability. A detailed summary of all variables, including symbols, units, and data sources, is provided in Table A5 of the Appendix. the paper uses the following production function:

$$LnEF = f\ (LnY, LnCE, LnFD, LnURB, LnHC, LnTI, LnR\&D, LnMC) \quad (1)$$

The production modelling framework can be written in the following:

$$LnEF_{it} = \emptyset_0 + \delta_1 LnY_{it} + \delta_2 LnCE_{it} + \delta_3 LnFD_{it} + \delta_4 LnURB_{it} + \delta_5 LnHC_{it} + \delta_6 LnTI_{it} + \delta_7 LnR\&D_{it} + \delta_8 LnMC_{it} + \varphi_{it} \quad (2)$$

Where i represents the countries, t indicates the period, and φ_{it} is the error term, respectively. $\emptyset_0$ is the constant, and δ_1, δ_2, δ_3, δ_4, δ_5, δ_6, δ_7, and δ_8 are the slope coefficients with respective variables.

5. Baseline Analysis

This section provides analysis of the baseline variables, including cross-section dependence and cross-sectional regression analysis of the variables used in the study between G5 and G7 economies. Tables 1 and 2 consider the extent to which real GDP, consumption expenditure, financial development, urbanization, human capital, technological innovation, R&D and market capitalization account for variation in the natural log of the ratio of the ecological footprint, but for differing groupings of countries (G5 in Table 1 and G7 in Table 2).

Table1. Regression captures cross-sectional dependence tests in G5 economies.

	GLS	PCSE
lnY	-0.426***(-3.34)	-0.426***(-3.03)
lnCE	0.172***(3.27)	0.172***(3.36)
lnFD	-0.617***(-2.96)	-0.617***(-2.72)
lnURB	-0.260(-1.06)	-0.260(-0.94)
lnHC	1.480***(5.04)	1.480***(5.39)
lnTI	0.563***(19.25)	0.563***(18.85)
LnR&D	0.352***(4.37)	0.352***(4.89)
lnMC	-0.208***(-5.33)	-0.208***(-5.24)
Constant	17.858***(24.95)	17.858***(25.53)
R^2		
N	125	125

The panel regressions estimated using the ecological footprint as the dependent variable from the G5 economies are presented in Table 1, applying both GLS and PCSE to a sample of 125 country-year observations. The two estimation methods provide nearly identical coefficients and significant t-statistics, confirming the stability of the results. For example, real GDP is statistically significant and it is the model with the estimated coefficient of –0.426 (t ≈ -3.34). This finding implies that a 1 percent increase in GDP results in a 0.426 percent decline of ecological footprints or it also means 0.426 percent increase in environmental quality. This negative correlation indicates that growth tends to reduce environmental damage if it is accompanied by cleaner technologies or stricter emissions standards.

There is, however, consumption expenditure with a positive elasticity of 0.172, indicating that a 1 percent increase in household consumption is associated with a rise of 0.17 percent in its ecological footprint. That is to say, higher consumption, if it is especially accompanied by non-green products, can impose pressures on the environment. Furthermore, financial development, however, exhibits large negative elasticity -0.617, indicating that a 1 percent expansion of the finance industry is related to 0.617 percent increase in environmental quality. Finally, urbanization has the estimated coefficient of -0.260, but is not significant, indicating that higher density cities also can act to both exacerbate local pollution through the congestion and the overuse of public facilities. However, since the coefficient is statistically insignificant, the impact is then not different from zero.

Human Capital, Technological Innovation and R&D are found to be the most powerful determinants of ecological footprint. Specifically, a 1-percent increase in human capital is found to increase the ecological footprint by 1.48 percent, which is the highest elasticity in the model, which leads to more environmental degradation. Furthermore, educated and skilled populations appear to contribute more to environmental regulation, the adoption of clean practices, and directing demand towards green products. Technology innovation brings an elasticity of 0.563, where a 1 percent increase in the innovation activity led to ecological footprint of 0.56 percent, while R&D expenditure increases the ecological footprints by 0.352. These numbers underscore the insignificance of patents, clean-technology, and research investments in reducing pollution intensity. Lastly, higher market capitalization is associated with a lower ecological footprint of -0.208, which means a one percent rise in market capitalization is related to a 0.208 percent rise in the ecological footprint, which reflects lower environmental quality.

Table2. Regression captures cross-sectional dependence tests in G7 economies.

	GLS	PCSE
lnY	2.615***(13.58)	2.615***(14.73)
lnCE	-0.109***(-4.55)	-0.109***(-6.15)
lnFD	0.607**(2.29)	0.607***(2.69)
lnURB	-4.298***(-8.19)	-4.298***(-6.88)
lnHC	-3.973***(-11.85)	-3.973***(-19.67)
lnTI	0.505***(15.78)	0.505***(21.65)

LnR&D	0.266(1.58)	0.266**(2.20)
lnMC	0.00012(0)	0.00012(0.00)
Constant	10.708***(2.96)	10.708***(3.51)
R^2		
N	150	150

Table 2 provides similar estimation as in Table 3 but for the case of G7 economies. The estimation covers 150 country- year observations and is also estimated by comparing the methods of GLS and PCSE. As shown in the table, real GDP has a strong and positive elasticity of 2.615, implying that a 1 percent rise in GDP is linked to a 2.6 percent increase in ecological footprints. This finding is consistent to that in G5 economies, indicating that real output imposes a negative impact on environmental quality both in developing and developed economies. In contrast, household cleaner energy consumption has a more negligible significant effect, where its elasticity is –0.109 and statistically significant at 5 percent significance level, which explains that a 1 percent increase in consumption spending translates into a 0.109 percent decrease in the ecological footprint, indicating that wealthier consumption patterns can partially improve the environmental quality.

Furthermore, financial development enters the model with a 0.607 elasticity and is statistically significant at 2 percent significance level, implying that an increase of 1 percent in the financial sector development would increase ecological footprint by about 0.61 percent. This positive correlation suggests that, everything else being equal, deeper banking and credit markets can deteriorate environmental quality. In contrast, the effect of urbanization displays an elastic profile on the dependent variable of -4.298, which is statistically significant at 1 percent significance level. Hence, a 1 percent increase in the share of the urban population indicates a 4.3 percent reduction in ecological footprints, which means improved environmental quality. This sizable effect likely captures the efficiency cost of urban density, public transit systems, and compact infrastructure, which can impact environmental quality.

Human capital appears another substantial environmental factor, yielding an elasticity of –3.973 and statistically significant at 1 percent significance level. This finding implies that an increase in education or skills of 1 percent would cause a reduction of 4.0 percent on the value of the ecological footprint, which implies an improved environmental quality. Furthermore, the influence of technological innovation is more subtle where it holds a positive elasticity of 0.505, indicating that a 1 percent growth in patenting or innovation is connected to a 0.505 percent, increase in ecological footprints. This finding suggests that new technologies are not necessarily beneficial for the climate or the environment if there are no explicit green innovation incentives; rather, they might also contribute to new types of resource use and emissions.

Research and development expenditure also has a slightly positive elasticity of 0.266 in case of the PCSE and it is statistically significant at 1 percent significance level, meaning that a 0.27 percent increase in the ecological footprint is caused by a 1 percent increase in R&D. In other words, research and development in G7 countries does not necessarily correspond to the improved environmental quality. Instead, the estimation shows that it is reducing ecological quality. Hence, R&D needs to be translated into the environmental domain, which may be expected to reduce the ecological footprint. In the final column, market capitalization has no sizable impact with the estimated coefficients approximately zero and not statistically significant at any levels, suggesting that the size of equity markets does not make the environmental pressures worse, nor does it make it better in the presence of the other variables.

In summary, on both tables, growth and finance are seen as double-edged swords, with their environmental impact being significantly country-specific, whereas technological innovation and R&D are two universally applicable determinants of ecological footprints. Specifically, growth has a positive impact on the environmental quality in G5 economies but a negative effect on G7 countries. Therefore, successful environmental strategies thus need to be sensitive to local stages of development. For example, the government can focus on promoting consumption-inducing policies in G7 economies while prioritize growth-inducing policies in G5 countries.

6. Robust Analysis

Table3. MM-QR for G5 economies.

Dependent variable: LnEF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
LnY	0.820*** (0.103)	0.808*** (0.089)	0.799*** (0.072)	0.790*** (0.065)	0.783*** (0.061)	0.775*** (0.067)	0.769*** (0.078)	0.762*** (0.089)	0.751*** (0.11)	0.748*** (0.14)
LnCE	-0.105*** (0.056)	-0.107*** (0.048)	-0.108*** (0.039)	-0.110*** (0.035)	-0.111*** (0.033)	-0.112*** (0.036)	-0.113*** (0.042)	-0.114*** (0.048)	-0.116*** (0.059)	-0.116*** (0.075)
LnFD	0.306** (0.104)	0.282** (0.09)	0.266*** (0.073)	0.246*** (0.065)	0.231*** (0.062)	0.216*** (0.067)	0.203** (0.078)	0.189** (0.09)	0.167 (0.11)	0.162 (0.141)
LnURB	-1.342*** (0.278)	-1.294*** (0.238)	-1.262*** (0.194)	-1.224*** (0.175)	-1.194*** (0.165)	-1.164*** (0.18)	-1.139*** (0.207)	-1.111*** (0.238)	-1.068*** (0.295)	-1.057*** (0.379)
lnHC	-1.294** (0.132)	-1.296*** (0.114)	-1.297*** (0.093)	-1.299*** (0.083)	-1.300*** (0.079)	-1.301*** (0.086)	-1.302*** (0.099)	-1.303*** (0.114)	-1.305** (0.14)	-1.305** (0.179)
LnTI	-0.064 (0.034)	-0.079* (0.03)	-0.089** (0.024)	-0.101*** (0.022)	-0.110*** (0.02)	-0.120*** (0.022)	-0.128*** (0.026)	-0.136*** (0.03)	-0.150*** (0.036)	-0.154*** (0.047)
LnR&D	-0.128 (0.067)	-0.09 (0.057)	-0.065 (0.047)	-0.034 (0.042)	-0.011 (0.04)	0.013 (0.043)	0.033 (0.05)	0.054 (0.058)	0.089 (0.071)	0.097 (0.091)
LnMC	-0.055** (0.023)	-0.051*** (0.019)	-0.048*** (0.016)	-0.045*** (0.014)	-0.043*** (0.014)	-0.041*** (0.015)	-0.039*** (0.017)	-0.036** (0.02)	-0.033* (0.024)	-0.032 (0.031)
N	150	150	150	150	150	150	150	150	150	150

As shown in Table 3, the quantile regression estimates for ecological footprint on its logged covariates in the G5 at ten quantiles (quantile 0.1 to 0.95), based on the moments, are presented in Table 5. From 150 observations, these estimates show how the relation between ecological footprints and some variables, including income, cleaner energy consumption, financial development, urbanization, human capital, technological innovation, research and development, and market capitalization.

As demonstrated in the table, real GDP enters positively and remains consistent across all quantiles between the 10th and 95th percentiles, with elasticities decreasing gently from 0.820 in the 10^{th} percentile to 0.748

in 95th percentile where all at a 1 percent significance level. This finding implies that a 1 percent gain in GDP leads to approximately a 0.75-0.82 percent increase in values of ecological footprints. On the other hand, cleaner energy expenditure negatively affects ecological footprint across quantiles in the entire interval, where the estimated coefficient is -0.105 in the 10th percentile and -0.116 in the 95th percentile, where all coefficients are significant at 1 percent in all quantiles. Specifically, a 1 percent increase in household consumption implies a 0.10-0.12 percent reduction in ecological footprints, highlighting the worsening impact of consumption expenditure on ecological footprints. This finding indicates that the negative impact of consumption is prevalent even across all quantiles.

In terms of financial development, the table demonstrates that the impact of financial development on the ecological footprint is positive, ranging from 0.306 in the 10th percentile to 0.162 in the 95th percentile, although the coefficients are not significant in the two highest percentiles. Furthermore, the statistical significance is also weakening from 1 percent to 5 percent significance level in the percentile of 70th and 80th and lost the significance in the 90th and 95th percentile. Furthermore, in terms of urbanization and human capital, both variables have large negative estimated coefficients in all quantile specifications. This finding indicates that higher rate or urbanization corresponds positively to the improved ecological footprint. This negative impact most likely comes from the overutilization of resources, which promotes degradation, as well as the increased consumption of fossil fuels, which deteriorates the quality of the environment. However, the negative impact of the urbanization effect decreases a little, which increases from -1.342 in the 10th quantile to -1.057 in 10th quantile, but it always remains significant at 1 percent. On the other hand, human capital remains relatively stable around -1.30, with the statistical significance at 1 percent for all quantiles. This effect suggests that a country with an additional urbanization of 1 percent decreases environmental pressures by approximately 1.06–1.34 percent, independent of whether or not its ecological footprint distribution is low or high.

In terms of technological innovation, the elasticity of innovation becomes more negative as we move up the quantiles. That is, at the 10th percentile, Technological innovation has the estimated coefficient of –0.064, while at the 50th percentile, the estimated coefficient is –0.120, and finally, the estimated coefficient is -0.154 at the 95th percentile. This gradient suggests that technological progress is increasingly important for mitigating ecological footprints, underlining the critical role of innovation in more polluted economies. On the other hand, in terms of R&D, the significant change comes from the lower quantiles, where the estimated coefficient is -0.128 at 10th percentile but it moves to 0.097 at the 95th percentile. However, across all quantiles, no statistical significance is found between R&D and ecological footprints. Finally, market capitalization consistently enters with a negative coefficient with the estimated coefficients migrating from –0.055 in the 10th percentile to -0.032 in the 95th percentile. Therefore, equity- market depth has little environmental improvement effect under low- ecological footprint levels, but the effect decreases and becomes insignificant under high- ecological footprint levels. In general, the results from

Table 5 show that the scale effect of growth and the mitigating effect of urbanization and human capital are consistent across the distribution of ecological footprint, whereas the roles of finance, innovation, and R&D are mostly different across various quantiles.

Table4. MM-QR for G7 economies.

Dependent variable: LnEF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
LnY	0.440*** (0.103)	0.446*** (0.089)	0.455*** (0.072)	0.460*** (0.065)	0.469*** (0.061)	0.477*** (0.067)	0.484*** (0.078)	0.489*** (0.089)	0.498*** (0.11)	0.510*** (0.14)
LnCE	-0.256*** (0.056)	-0.254*** (0.048)	-0.250*** (0.039)	-0.248*** (0.035)	-0.245*** (0.033)	-0.242*** (0.036)	-0.239*** (0.042)	-0.237*** (0.048)	-0.233*** (0.059)	-0.229*** (0.075)
LnFD	-0.230** (0.104)	-0.230** (0.09)	-0.230*** (0.073)	-0.229*** (0.065)	-0.229*** (0.062)	-0.229*** (0.067)	-0.229*** (0.078)	-0.229** (0.09)	-0.229** (0.11)	-0.229 (0.141)
LnURB	0.038 (0.278)	0.009 (0.238)	-0.031 (0.194)	-0.057 (0.175)	-0.094 (0.165)	-0.132 (0.18)	-0.164 (0.207)	-0.191 (0.238)	-0.231 (0.295)	-0.284 (0.379)
lnHC	0.316** (0.132)	0.318*** (0.114)	0.320*** (0.093)	0.321*** (0.083)	0.323*** (0.079)	0.324*** (0.086)	0.326*** (0.099)	0.327*** (0.114)	0.329** (0.14)	0.332* (0.179)
LnTI	0.001 (0.034)	0.002 (0.03)	0.004 (0.024)	0.005 (0.022)	0.007 (0.02)	0.009 (0.022)	0.010 (0.026)	0.011 (0.03)	0.013 (0.036)	0.016 (0.047)
LnR&D	-0.004 (0.067)	0.000 (0.057)	0.006 (0.047)	0.010 (0.042)	0.016 (0.04)	0.021 (0.043)	0.026 (0.05)	0.030 (0.058)	0.036 (0.071)	0.044 (0.091)
LnMC	0.023 (0.023)	0.020 (0.019)	0.016 (0.016)	0.013 (0.014)	0.009 (0.014)	0.005 (0.015)	0.002 (0.017)	-0.001 (0.02)	-0.006 (0.024)	-0.011 (0.031)
N	125	125	125	125	125	125	125	125	125	125

Table 4 describes the quantile regression for the case of G7 economy based on 125 observations occurring at nine quantiles. In case of G7 economies, Real GDP is positively and statistically significant at every quantile, increasing constantly from 0.440 at the 10th quantile to 0.510 at the 95th quantile. This finding implies that the increase in GDP of 1 percent is associated with about 0.44 percent increase of ecological footprints, when the footprints were initially low, while the impact increases to 0.51 percent when the footprints were high. The upward trend of these quantile- specific elasticities suggests that the scale- effect of real output on ecological footprints is strengthening as the level at which the environmental damage is increasing. Household cleaner energy consumption has a uniformly negative and statistically significant across all quantiles as well, ranging from -0.256 at 10^{th} percentile to -0.229 at 95^{th} percentile, all significant at least at the 5 percent level. This finding implies that an increase of 1 percent in the consumption expenditure reduces the ecological footprints between 0.23 percent and 0.26 percent in high and low ecological footprint countries, respectively. This finding also indicates that greener patterns of consumption reduce ecological stress steadily across all regimes.

Contrary to our G5 results, financial development in G7 economies has a significant negative effect by -0.230 at all quantiles. This finding implies that a one percent increase in financial development corresponds to a reduction by around 0.23 percent in ecological footprints, which correspond to better environmental quality. On the other hand, the coefficients for urbanization in G7 economies range from 0.038 at 10th percentile to -0.284 at 95th percentile, with none of these estimates being statistically significant. This finding implies that the efficiency gains from urban density have no significant impact on environmental quality in the G7 economies. On the other hand, the estimated elasticity of human capital is uniformly positive and strong, increasing in magnitude, ranging from 0.316 at 10 percent percentile to 0.332 at 95th percentile. This finding implies that an increase in skills by 1 percent generates 0.32 - 0.33 percent increase in the ecological footprint, which may indicate the dependency of skill development on non-green energy utilization.

In terms of technological innovation, the estimation demonstrates that its estimated impact on ecological footprints is 0.001 at 10th percentile to 0.016 at 95th percentile. However, given no statistical significance, this finding implies that the innovation provides no significant impact on the ecological footprints, either in low or high ecological footprints economies. Similarly, R&D expenditure shifts from –0.004 at 10th percentile to 0.044 at 95th percentile but with no statistical significance. This finding suggests that innovation and R&D need to be more enhanced to provide significant environmental impacts on environmental quality. Finally, market capitalization exhibits small and insignificant effects, which range from 0.023 at 10 percent percentile to −0.011 at 96th percentile but without any statistical significance. This finding implies that market capitalization has no significant impact on the environmental quality, either in high or low ecological footprints economies.

In summary, the results of the quantile- regression for the G5 (Table 5) and G7 (Table 6) provide some different results. First, although both tables highlight a strong scale effect of output on environmental pressures, they result in different trends. As the quantile increases, the impact of output on ecological footprints in developing economies is decreasing while it is increasing in developed economies. This finding is consistent with the EKC literature such as Ahmed et al. (2020b), Wang et al. (2024) and Sharma et al. (2021) where they demonstrate an inverted U curve for the EKC relationship. Hence, the negative impact of association between output and ecological footprint in G5 economies is the early stage before it reaches the peak point and the relationship turns into positive, as is is found in the G7 economy. Second, consumption expenditure performs as an environmental break in both groups, with a negative elasticity across all quantiles, which align with Wang et al. (2023) arguing that consumption patterns shift towards greener products, potentially reducing ecological footprints. Third, in terms of financial development, in G5 economies, greater financial developments can impose negatively to damages the environment at lower and middle quantiles. On the contrary, G7 financial deepening has a uniformly positive effect to environmental quality through a reduction of ecological footprints across all quantiles. This mixed finding is also consistent with the literature where the existing literature demonstrates a mixed relationship between financial development and ecological footprint, such as Topcu et al. (2020) and Younis et al. (2021), which argue the positive impact, and Asiedu (2024), which demonstrates a negative impact. Fourth, in terms or urbanization, the impact of urbanization on environmental quality is positive in G5 economies, while it is insignificant in G7 economies. It is consist with Sarwar et al. (2024) where urbanization can reduce ecological footprint if managed sustainably. Furthermore, there is a positive human capital effect in both economies, but with very different signs. The impact of human capital is reducing ecological footprints for the G5, but it is increasing ecological footprints in G7 economies which is consistent with past findings from Yu and Guo (2023) and Wang et al. (2023), but it is increasing ecological footprints in G7 economies, which is consistent with the mixed finding from Chen et al. (2022) and Gu et al. (2024). This finding is also consistent with past literature demonstrating a mixed finding. In case of G5 economies, the finding follows Chen et al. (2022) and Gu et al. (2024) demonstrating mixed effect, while in case of developed G7 economies, the finding is consistent with Yu and Guo (2023) and Wang et al. (2023). As for technological innovation and R&D expenditure, the study demonstrates quantiles, implying that without clear environmental focus, neither the quantity of patents nor the R&D expenditure systematically induces environmental quality. Finally, market capitalization has a small positive impact on the G5 economies, which is aligned with a reducing impact in Asiedu (2024), while the impact is insignificant in G7 economies.

7. Policy Discussions

The empirical results from the G5 and G7 estimation point out the imperative need for policy frameworks that involve various variables within its policy formulation, including human capital, technological innovation, consumption expenditure, urbanization, R&D expenditure, and market capitalization. Based on the findings, authorities can focus on formulating policies as follows. First, as there is economically significant cross-sectional dependence in almost all the socio- economic variables, policy makers need to incorporate the information regarding regional policy development. This comprehensiveness is expected to improve the policy effectiveness in improving the country's environmental quality. Furthermore, involving policy development at regional level also ensures that domestic policy decisions capture not just domestic conditions, but also spillovers and feedback from closely synchronized business and financial cycles.

Second, the difference in the sign of the real GDP impact in the G5 economies and the G7 economies shows that the environmental effect of growth is highly region-specific. That is, G5 economies experience a positive impact of real output growth on environmental quality, while the impact is detrimental in G7 economies. Therefore, policymakers must formulate comprehensive policies associated with cleaner technologies, more stringent emission standards, and green- lending standards to limit resource- intensive activities to ensure that real output imposes a positive impact on environmental quality. Third, urbanization in G5 economies demonstrate a negative impact on ecological footprints, which promotes environmental quality. However, the impact magnitude is diminishing as the quantile increases, indicating that policymakers need to focus on improving urbanization policy in the upper quantile. Urbanization policy can be improved by complementing the policy with green technology. As for G7 economies, although urbanization has no significant impact on ecological footprint, the coefficients sign is positive, which corresponds to lower environmental quality. Thus, the authorities need to enhance urbanization policy to ensure that higher population density from urban to city is not followed by the rising environmental degradation.

Fourth, in terms of financial development, the deepening of credit and equity markets in advanced economies is associated with higher ecological footprints and thus lower environmental quality. Therefore, policymakers need to investigate the issue and formulate policies to isolate the negative impact of financial development. One of the strategies is by promoting capital- reserve treatments for green loans, turning financial "deepening" into a positive environmental force. As in emerging economies, on the other hand, deeper financial development is associated with lower ecological footprints and corresponds to higher environmental quality where the magnitude is identical across quantiles. In this situation, policymakers should mandate environmental stress tests for banks, work pollution impact rankings into lending tasks and create green bond markets to fund cleaner infrastructure. Finally, technological innovation in emerging countries have a positive impact on environmental quality, but it is still insignificant in the 10th percentile. This indicates that the authority needs to ensure the homogenous positive impact of the innovation on environmental quality towards across all quantiles. This can be done by complementing the innovation with green-technology or refocusing the innovation towards green innovation.

8. Conclusion

This study is interested in understanding the impact of economic and financial variables on ecological footprints across G5 (developing) and G7 (developed) economies. The study involves data from these two regional economies covering ecological footprints, real GDP, consumption, financial development, urbanization, human capital, technological innovation, R&D expenditure and market capitalization. The dependent variable in the estimation in this study is ecological footprints, which reflect the amount of energy consumed. The estimation is conducted using by method of moment quantile regression (MM-QR), separately between G5 and G7 economies. Before the estimation method is applied, the study also implemented the cross-dependency test, which provides a finding that the dynamics of variable used is dependent on the dynamics of the peer countries in the same region.

The estimation in the study demonstrates some interesting findings. First, the impact of output on ecological footprints in developing economies is decreasing while it is increasing in developed economies. Second, consumption expenditure performs as an environmental break in both groups, with a negative elasticity across all quantiles, indicating a positive impact on environmental quality both emerging and developed countries. Third, in terms of financial development, in G5 economies, greater financial developments can impose negatively to damage the environment at lower and middle quantiles. On the contrary, G7 financial deepening has a uniformly positive effect to environmental quality through a reduction of ecological footprints across all quantiles. Fourth, in terms or urbanization, the impact of urbanization on environmental quality is positive in G5 economies, while it is insignificant in G7 economies. Furthermore, the impact of human capital is reducing ecological footprints for the G5, but it is increasing ecological footprints in G7 economies. As for technological innovation and R&D expenditure, the study demonstrates that without clear environmental focus, neither the quantity of patents nor the R&D expenditure systematically induces environmental quality. Finally, market capitalization has a small positive impact on the G5 economies, while the impact is insignificant in G7 economies.

Appendix

TableA1. Correlation for G5 economies.

	lnEF	LnY	lnCE	LnFD	lnURB	lnHC	lnTI	LnR&D	lnMC
LnEF	1								
LnY	-0.3001	1							
LnCE	0.2954	-0.5122	1						
LnFD	0.2515	0.1899	0.1304	1					
LnURB	-0.5172	0.9143	-0.3168	0.1078	1				
LnHC	-0.091	0.7939	-0.5612	0.4034	0.6638	1			
LnTI	0.9024	0.0525	0.0248	0.4003	-0.2422	0.2067	1		
LnR&D	0.6257	-0.0067	0.3021	0.7411	-0.1487	0.0489	0.6791	1	
LnMC	-0.3099	-0.044	-0.2595	0.4753	-0.077	0.0686	-0.1798	0.1942	1

TableA2. correlation for G7 economies.

	lnEF	LnY	lnCE	LnFD	lnURB	lnHC	lnTI	LnR&D	lnMC
lnEF	1								
lnY	0.5671	1							
lnCE	-0.173	0.1478	1						
lnFD	0.332	0.6783	-0.0613	1					
lnURB	0.0947	0.0632	-0.0197	0.4856	1				
lnHC	0.257	0.6072	-0.0286	0.5396	0.2858	1			
lnTI	0.8033	0.2645	-0.1825	0.2322	0.4392	0.3765	1		
LnR&D	0.5435	-0.0708	0.0515	-0.1238	0.3079	0.0075	0.7556	1	
lnMC	0.1912	0.5133	0.0133	0.6373	0.34	0.2978	0.0854	-0.3235	1

TableA3. Summary statistics for G5 economies.

Variable	Obs	Mean	Std. dev.	Min	Max
lnEF	125	20.28625	1.050224	18.74772	22.36196
lnY	125	8.421351	0.816355	6.47998	9.245531
lnCE	125	3.009253	0.671032	2.043814	3.913023
lnFD	125	-0.80081	0.21892	-1.31	-0.40048
lnURB	125	4.013398	0.391021	3.289036	4.466712
lnHC	120	0.843781	0.14079	0.494881	1.128624
lnTI	125	10.17992	1.431568	8.051978	14.27651
LnR&D	124	-0.2462	0.508659	-1.38362	0.875469
lnMC	125	4.054875	0.775831	2.580974	5.776757

TableA4. Summary statistics for G7 economies.

Variable	Obs	Mean	Std. dev.	Min	Max
lnEF	150	20.09364	0.791601	19.26274	21.8557
lnY	150	10.58803	0.168775	10.31088	11.01367
lnCE	150	2.009676	0.82909	-0.16252	3.171784
lnFD	150	-0.22166	0.120143	-0.65108	-0.04523
lnURB	150	4.38577	0.049731	4.305861	4.519394
lnHC	144	1.24897	0.072503	1.049116	1.328029
lnTI	150	11.1899	1.273922	9.568924	13.33982
LnR&D	150	0.822552	0.244599	0.427748	1.230479
lnMC	150	4.488289	0.486583	2.308157	5.363546

TableA5. Variable description.

Variables	Symbols	Units of the variables and Details	Data Sources
Ecological Footprint	EF	EF is measured as an aggregate of the demand and supply side factors - cropland, grazing land, forest land, fishing grounds and built-up land. The unit of EF is global Hectares (gha).	Global Footprint Network
Per Capita Income	Y	GDP Per Capita constant 2015 US dollar	World Bank Development Indicators (WDI)
R&D Expenditure	RD	As a percentage of GDP	
Technological Innovation	TI	Sum of resident and non-resident patent applications	

Clean Energy Consumption	CE	Renewable energy consumption (% of total final energy consumption)	
Market Capitalisation	MC	Market Capitalisation of Listed Domestic companies as % of GDP	
Financial Development Index (FDI)	FDI	FDI is a measure of depth, access and efficiency of financial institutions and financial markets. 1 represents the countries with best financial position while 0 represents countries with poor financial position.	International Monetary Fund (IMF)
Human Capital Index (HCI)	HCI	HCI is an index per person based on average years of schooling and returns to education	Penn World Table Version 10.01

TableA6. Cross-sectional dependence test for G5 economies.

Variables	***Pesaran (2015) Cross-section dependence	
	Statistic	p-value
lnEF	9.454	0.000
lnY	14.193	0.000
lnCE	6.309	0.000
lnFD	12.386	0.000
lnURB	13.679	0.000
lnHC	15.368	0.000
lnTI	10.389	0.000
LnR&D	6.128	0.000
lnMC	11.025	0.000

TableA7. Cross-sectional dependence test for G7 economies.

Variables	***Pesaran (2015) Cross-section dependence	
	Statistics	p-value
lnEF	10.131	0.000
lnY	18.174	0.000
lnCE	14.166	0.000
lnFD	12.184	0.000
lnURB	18.582	0.000
lnHC	18.688	0.000
lnTI	1.13	0.258
LnR&D	5.886	0.000

lnMC	8.519	0.000

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