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Economic Growth, Demographic Change, Energy Consumption, and Vegetation Degradation in Pakistan: ARDL Evidence on the Energy–Environment Nexus

Sonia Nisar[1], Mukamil Shah[2]

[1] PhD Scholar, Institute of Management Sciences, Peshawar, Pakistan. Email: sonyanisar@gmail.com
[2] Assistant Professor of Economics, Institute of Management Sciences, Peshawar, Pakistan.
Email: mukamil.shah@ims.edu.pk

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ABSTRACT

While research on ecological sustainability in developing economies is usually concerned with the quantity of carbon dioxide (CO2) emissions in the atmosphere, land use change and deforestation are important, real-time indicators of environmental degradation. The present study examines the interdependence between these parameters of economic growth, population growth, urbanization, energy use and carbon emissions associated with the presence of vegetation cover in Pakistan in the period 1990-2025. Both short and long run equilibrium relationships are explored using time-series, World Development Indicators (WDI) data and an autoregressive distributed lag (ARDL) bounds testing model with small-sample critical value corrections. With the addition of the quadratic income specification the study rigorously examines the Environmental Kuznets Curve (EKC) hypothesis for vegetative degradation. The results of this empirical study confirm a strong cointegration relationship between the variables. Substantial negative effects are caused by energy use, urbanization, and population growth. According to short-run error correction mechanism, there will be a quick adjustment to the long-run equilibrium after external shocks. The findings revealed the need for a complementary approach that integrates indicators from the atmosphere and the land to develop policies and strategies for environmental and energy transitions and environmentally sustainable urban development in Pakistan.

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Corresponding Author's Email: sonyanisar@gmail.com
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1. Introduction

Rapid population growth, energy intensive economic activities, unplanned urban growth, and rapid industrialization cause ecological stress in emerging economies such as Pakistan because of economic development and environmental integrity. There are some development trajectories that are not conducive to ecological quality and sustainability, both in agriculture and urbanization (Ali & Rahman, 2024). However, Population Growth and urbanization put enormous pressure on land resources in Pakistan (Adanma & Ogunbiyi, 2024). In empirical research, traditionally, the main measure of environmental degradation has been the production of carbon dioxide emissions. The use of fossil fuels can be seen as immediate environmental impact in areas of rapid industrialization through CO2 emissions (Wang et al., 2016). The use of fossil fuels is directly linked to economic output trends (Shakeel, 2021). Energy consumption is a key intermediate link between economic growth and emissions (Wang et al., 2016; Wen et al., 2021). Furthermore, any rise in energy

consumption can result in a disproportionately high rise in carbon concentrations (Sadiq et al., 2023). But these assessments of the atmosphere only reflect part of the damage caused by economic development to the ecology. The importance of land-use change, deforestation and vegetation loss as an important aspect of environmental degradation that is not captured in the traditional emissions metrics has been highlighted in recent literature. In less industrialized areas, land-cover changes are usually the main source of ecological stress, instead of industrial pollution (Ekka et al., 2023). Increased population leads to land use change and reduces vegetation resilience (Mir et al., 2025).

Moreover, land-use indicators are critical to supplement emission-based evaluations, which will lead to a more comprehensive assessment of environmental damage (Guo et al., 2024). The studies on urban corridors in Pakistan, including Islamabad, Rawalpindi, and Lahore, reveal that urban expansion has caused a substantial loss in the green spaces and forest carbon stocks in the city (Khan, 2013; Mannan et al., 2021). The empirical basis of this study is illustrated in the figure below which shows a negative correlation between urbanization and reduction in vegetation cover in Pakistan during the last few decades.

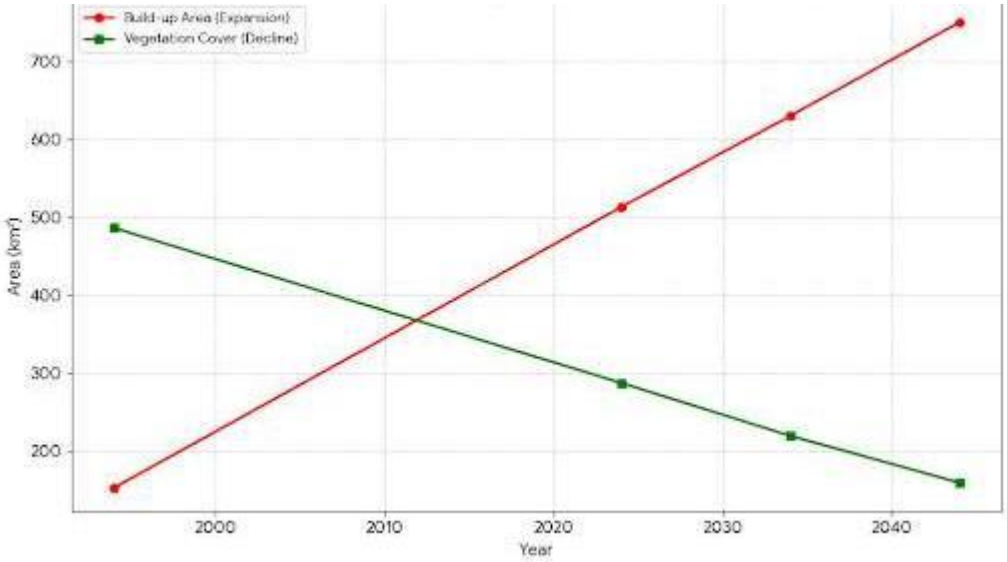


Figure 1: Historical and Projected Land Use Trends in Pakistan (1994–2044) Build-up Area Expansion vs. Vegetation Cover Decline

Past studies in Pakistan have mainly concentrated on CO2 as the only environmental quality indicator without considering urbanization and population growth as key factors of ecological stress. This limited perspective fails to consider land-use impacts on the environment, such as deforestation, loss of vegetation and degradation of ecosystems, and assumes population growth and urbanization are "control variables" and not significant environmental stressors. Banzhaf et al. (2022) argue for the use of "multifaceted" and "context-specific" metrics that more accurately reflect these pressures, but the absence of any national-level study that incorporates vegetation cover as a critical structural variable in addition to urbanization, population growth, and real GDP in a single macroeconomic model. The speed of ecological adjustment, which is the rate of change in vegetation cover following an economic shock, is also relatively unexplored in the context of Pakistan. This study tackles these gaps in three ways: first, it transcends the conventional growth-environment indicator of emissions to one based on land use, ecological stress; second, it shifts the focus from the role of urbanization and population growth as controls to that of primary structural determinants; and, third, using the ARDL bounds testing method (Pesaran et al., 2001) on Pakistan's time series (1990-2025), it presents new evidence regarding the rate at which the vegetation cover returns to equilibrium after an economic shock.

2. Literature Review and Theoretical Framework

There has been a wide range of studies on the association between economic growth and environmental quality and the Environmental Kuznets Curve (EKC) hypothesis has played a significant role in these studies. Dinda (2005) provides a theoretical underpinning for the inverted-U relationship where increasing income leads to changes in the industrial structure, changes in consumer preferences, and changes in the capacity of the regulators. Building on this, Zhang et al. (2022) further explore this in a systems thinking context to point to feedback relationships between growth, energy consumption and ecological deterioration, particularly in developing countries. In Pakistan, Manzoor et al. (2025) use the ARDL and NARDL methods to demonstrate that Pakistan is still in the ascending phase of the EKC, wherein economic development and energy consumption drive up emissions but fail to improve the environment. These results are further supported by Ali and Rahman (2024) who reported that if not structural changes, growth will exacerbate ecological strains. Energy Consumption plays vital role in the growth-environment relationship. Energy is considered as critical in industrial, transport, and domestic sectors by Wang et al. (2016) and there is a positive strong relation between energy consumption and economic growth at the global level according to Sharma (2010).

However, there are also some environmental costs associated with the use of fossil fuels: Mohsin et al. (2019) report high co-movement between energy use and CO2 emissions for the transport sector in Pakistan, and Wen et al. (2021) note that lag of renewable and energy-efficient technologies adoption worsens the growth-energy relationship in developing countries. Similarly, Sadiq et al. (2023) find that the ASEAN context can also have strong emission impacts, especially for small energy consumption increases, which is similar to energy consumption composition in Pakistan. Population growth and urbanization are major factors that influence the impact on the environment (Rehman et al., 2021). The more industry that is active the more economic output is generated, but the more economic output is generated the more environmental quality is reduced by increased resource utilization, and the more urban development takes place, the greater the pressures on environmental quality due to increased energy consumption and growing transport networks. The IPAT model reveals the interaction between population size, affluence, and technological efficiency and how this impacts environmental degradation, especially in Pakistan, where increasing population and affluence increases the demand for energy, shelter, and food, which puts pressure on the natural resources and drives land-cover change Ehrlich and Holdren (1971). Recent analyses go beyond the emission focused approach to environmental degradation and highlight the importance of land-use change. Deforestation and vegetation loss are recognized as major ecological issues by Pongratz et al. (2021), and Huang et al. (2024) consider vegetation cover as an important component for carbon sequestration and regulating local climate. Green spaces are also a diminishing resource in the cities of Pakistan, particularly in Rawalpindi as shown by earlier studies by Khan (2013) and Mannan et al. (2021) which indicate a trend across the country. Mir et al. (2025) show that population pressure is the major factor in land-use change, and therefore that it is important to study demographic variables as part of environmental growth models, and not as an add-on.

There has been an increasing volume of literature that incorporates ecological indicators into the models of growth and the environment. Guo et al. (2024) demonstrate the potential of using land-quality metrics derived from remote sensing data to supplement emission data, especially within river deltas in China, where Abulibdeh et al. (2024) study a comparable framework to arid urban areas by linking land surface temperature and carbon footprint to building energy consumption. In the context of the agriculture, Kamyab et al. (2024) discuss the carbon dynamics in agriculture and make parallels with changes in vegetation cover in agrarian economies like Pakistan. Taken together, these studies indicate that the combination of atmospheric and terrestrial measures of environmental stress has greater ecological meaning to the developing economies compared to either measure alone. However, the literature on Pakistan is still missing an important aspect: the vegetation cover has not been included as a major structural variable in a national level macro-economic model, which also incorporates population growth, urbanization, energy consumption and real Gross Domestic Product (GDP); also, the rate at which vegetation cover is recovered after

the occurrence of an economic shock has not been thoroughly analyzed. This study aims to tackle both these issues using the ARDL bounds testing methodology along with an analytical framework that focuses on the vegetation.

3. Methodology

3.1. Data and Variables

Annual time-series data for Pakistan (1990–2025, 36 observations) were retrieved from the World Development Indicators (WDI) database World (2026).

Table 1
Variables, Definitions, WDI Codes, and Summary Statistics

Variable	Symbol	WDI Series Code	Measurement Unit	Mean	Std. Dev.
Vegetation Cover	VC	AG.LND.FRST.ZS	Forest area (% of total land area)	5.480	0.562
Urbanization	URB	SP.URB.TOTL.IN.ZS	Urban population (% of total)	34.515	2.300
Population Growth	LPG	SP.POP.GROW	Annual population growth rate (%)	0.340	0.124
Real GDP per Capita	LEG	NY.GDP.PCAP.KD	Constant 2015 US$ (natural log)	0.505	0.400
Energy Consumption	LEC	EG.USE.PCAP.KG.OE	kg of oil equivalent per capita (log)	2.629	0.031
Carbon Emissions	CO2	EN.ATM.CO2E.PC	Metric tons per capita (natural log)	0.731	0.124

Vegetation cover is calculated here specifically as forest area, rather than a broader composite of all vegetated land; this narrower, WDI-consistent definition is used throughout so that the empirical results can be interpreted against a single, clearly defined indicator. Table 1 displays that Pakistan's forest cover has persistently low and relatively stable over the sample period, consistent with the country's long-standing status as forest-poor, while urbanization and energy consumption show the widest variation among the regressors, reflecting the structural changes the economy underwent between 1990 and 2025.

3.2. Model Specification

The EKC framework, the functional model is specified as:

$$VC = f(LEG, LEG^2, LEC, URB, LPG, CO2)$$

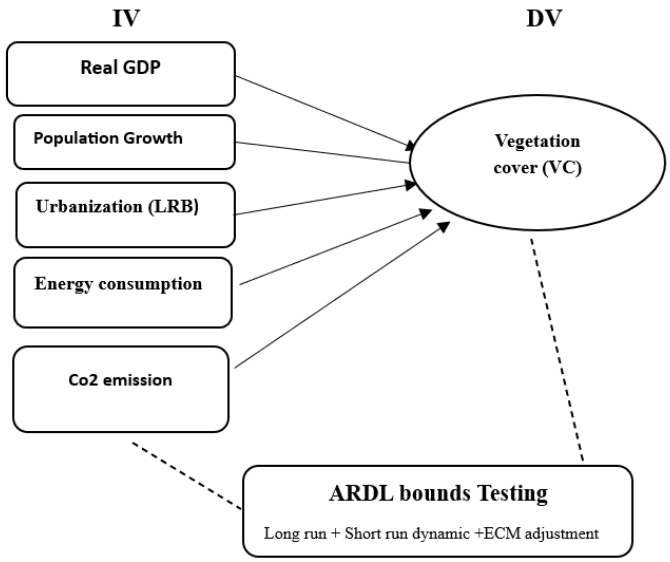


Figure 2: Conceptual Framework of Drivers of Vegetation Cover Decline in Pakistan

The earlier research Guo et al. (2024); Mir et al. (2025); Pongratz et al. (2021) follows this specification in which vegetation cover was used as an ecological outcome affected by economic, demographic, and energy-related structural forces, with a quadratic real GDP term added to allow a formal test of the Environmental Kuznets Curve.

The Unrestricted Error Correction Model (UECM) for ARDL bounds testing is given by Equation 1:

$$\Delta VC_t = \beta_0 + \sum_i \beta_{1i}\,\Delta VC_{t-i} + \sum_i \beta_{2i}\,\Delta LEG_{t-i} + \sum_i \beta_{3i}\,\Delta(LEG^2)_{t-i} + \sum_i \beta_{4i}\,\Delta LEC_{t-i} + \sum_i \beta_{5i}\,\Delta URB_{t-i} + \sum_i \beta_{6i}\,\Delta LPG_{t-i} + \sum_i \beta_{7i}\,\Delta CO_{2,t-i} + \lambda_1 VC_{t-1} + \lambda_2 LEG_{t-1} + \lambda_3 (LEG^2)_{t-1} + \lambda_4 LEC_{t-1} + \lambda_5 URB_{t-1} + \lambda_6 LPG_{t-1} + \lambda_7 CO_{2,t-1} + \varepsilon_t \quad (1)$$

The ECM specification is expressed as Equation 2:

$$\Delta VC_t = \alpha_0 + \sum_i \alpha_{1i}\,\Delta VC_{t-i} + \sum_i \alpha_{2i}\,\Delta LEG_{t-i} + \sum_i \alpha_{3i}\,\Delta(LEG^2)_{t-i} + \sum_i \alpha_{4i}\,\Delta LEC_{t-i} + \sum_i \alpha_{5i}\,\Delta URB_{t-i} + \sum_i \alpha_{6i}\,\Delta LPG_{t-i} + \sum_i \alpha_{7i}\,\Delta CO_{2,t-i} + \phi ECT_{t-1} + \mu_t \quad (2)$$

4. Empirical Results

Table 2

ADF and Phillips–Perron Unit Root Tests

Variable	ADF Level	ADF 1st Diff	PP Level	PP 1st Diff	Order of Integration
VC	-1.821	-4.215***	-1.789	-4.310***	I(1)
URB	-0.114	-3.892***	-0.105	-3.910***	I(1)
LPG	-3.125**	—	-3.150**	—	I(0)
LEG	-1.452	-4.012***	-1.420	-4.050***	I(1)
LEC	-1.980	-4.512***	-1.950	-4.580***	I(1)
CO2	-2.110	-4.105***	-2.080	-4.120***	I(1)

*Note: *** and ** indicate significance at 1% and 5% levels, respectively.*

Both the ADF and PP tests approve on the order of integration for every variable: Population Growth is stationary at level, I(0), while the remaining five variables are stationary only after first differencing, I(1) (Dickey & Fuller, 1979; Phillips & Perron, 1988). Since no variable is integrated of order two, I(2), the series satisfy the precondition for ARDL bounds testing, which requires a mix of I(0) and I(1) regressors rather than any higher order of integration.

Table 3

Long-Run ARDL Coefficients

Variable	Coefficient	Std. Error	t-Statistic	p-value
URB	-0.178	0.041	-4.34	0.000
LPG	-0.388	0.162	-2.39	0.022
LEG	-0.054	0.063	-0.86	0.396
LEG2	-0.012	0.015	-0.80	0.428
LEC	-2.805	0.925	-3.03	0.005
CO2	-0.334	0.158	-2.11	0.042
Constant	+18.973	3.210	5.91	0.000

F-Bounds Test: F = 8.966 (exceeds the 1% upper bound of 4.15; also exceeds the Narayan small-sample critical value) Narayan (2005).

Table 4

Short-Run Error Correction Model (ECM) Results

Variable	Coefficient	Std. Error	t-Statistic	p-value
ΔURB	-0.086	0.034	-2.53	0.018
ΔLPG	-0.172	0.079	-2.18	0.038
ΔLEG	-0.021	0.031	-0.68	0.503
ΔLEC	-1.124	0.408	-2.75	0.011
ΔCO2	-0.141	0.062	-2.27	0.031
ECT(-1)	-0.611	0.098	-6.24	0.000

The short-run coefficients broadly mirror the long-run results in sign, with urbanization, population growth, energy consumption, and carbon emissions all significantly negative, while real GDP remains insignificant in the short run as well. The error correction term, ECT(-1), is negative and highly significant at −0.611, indicating that roughly 61% of any short-run deviation from the long-run equilibrium between vegetation cover and its determinants is corrected within a single year.

Table 5
Diagnostic Tests

Test	Statistic	p-value	Decision
Breusch-Godfrey LM	0.259	0.995	No Serial Correlation
Breusch-Pagan-Godfrey	1.823	0.230	Homoskedastic
Ramsey RESET	0.812	0.374	Model Correctly Specified
Jarque-Bera Normality	2.008	0.366	Residuals Normal

The model satisfies every diagnostic test at conventional significance levels: the high p-values on the Breusch-Godfrey and Breusch-Pagan-Godfrey tests indicates the null hypotheses of no serial correlation and constant-variance residuals cannot be rejected, the Ramsey RESET test confirms the model is correctly specified, and the Jarque-Bera test means the residuals are normally distributed. Together, these results indicate that the standard errors underlying the long-run and short-run coefficients reported above are valid for inference.

5. Discussion

Results of the study give a coherent picture of the factors associated with ecological degradation in Pakistan in terms of vegetation cover. Consistent with the results of Mir et al. (2025), who reported that vegetative land resources were losing in South Asia due to the population growth, and Guo et al. (2024), who reported that increasing urbanization was a negative factor affecting land resources in South China, urbanization and population growth were also identified as important structure-related negative factors affecting vegetative land resources. Furthermore, the estimated coefficient of energy consumption is the largest of all the variables considered, consistent with the findings of Wen et al. (2021) and Mohsin et al. (2019) in the context of other developing economies and Pakistan's ecological growth path, which is still reliant on a fossil fuel intensive growth path; therefore, the magnitude of the coefficient is not given the significance of a ranking of relative importance. The carbon emissions are also related to long-term vegetation loss, which is consistent with the relation between emissions and land degradation found by Pongratz et al. (2021).

This study is the first ARDL/NARDL study that incorporates a quadratic real GDP term (LEG2) with the linear term, thus formalizing a test for the Environmental Kuznets Curve hypothesis from the perspective of vegetation cover for Pakistan while Manzoor et al. (2025) use a linear specification. The results show that both linear and quadratic GDP term are not statistically significant in the long run, which suggests that either there is no EKC turning point for land degradation in Pakistan or the turning point was not reached in the country; this is similar to Ali and Rahman (2024) who warn that when there is growth, it does not necessarily bring an observable improvement in land degradation. Disequilibrium could be corrected in a single year (61.1%), reflecting a dynamic ecological system, suggesting that long-term impacts may still be further optimized by policy interventions that are sustained and well targeted. In general, the findings suggest that Pakistan's development trajectory is still energy-intensive and focused on urban and industrial growth, while there is a need for an integrated management of land use, demographic pressures and energy systems to achieve ecological sustainability.

6. Conclusion and Policy Implications

This research offers new empirical findings of the impact of economic growth, energy use, urbanization and demographic changes on the ecological implications of land use in Pakistan. Vegetation cover was featured as the primary environmental indicator in an ARDL

bounds-testing framework and a quadratic specification on GDP was tested, bringing to light land-based aspects of degradation that are typically ignored in traditional emission-based modelling. The long run period of the study revealed that urbanization and population growth are most significant with vegetation loss followed by energy use and carbon emissions, whereas neither the linear nor the quadratic real GDP terms are significant, suggesting that there is no turning point in the Environmental Kuznets Curve for vegetation cover in Pakistan. The research also demonstrates that the growth-environment relationship in Pakistan is co-integrating and dynamically flexible in the long-run, as the mechanism of error correction is rapid, that is, the negative deviation from the long run is corrected rapidly by about 61% within one year. The findings suggest three points that future policy and research need to take note of. First, national environmental governance only takes a look at emission reduction targets, but no consideration for ecological degradation due to land use. Secondly, in Pakistan, urban planning does not have a strict ecological impact assessments that would safeguard the green spaces even in the process of approval of a new urban development project. Third, energy policy remains focused on increasing supply rather than changing the structure of energy use including a focus on renewable energy which results in maintaining the energy intensive growth pattern described as one of the key drivers of vegetation loss.

In light of the findings, the subsequent recommendations are made, the Institutionalization of sustainable land use management at national level, with clear targets on vegetation cover in provincial development plans and with regular monitoring by remote sensing. Additionally, the establishment of minimum green space ratios and ecological buffer zones around metropolitan regions experiencing growth, as required by compulsory urban planning regulations, is justified. If we are to weaken the relationship between economic growth and ecological degradation on land, then a credible transition from fossil fuels to renewable energy, in particular solar and wind, is required. Increased investment in girls' education, reproductive health services and rural economic development can help to alleviate the demographic pressures discussed here as an important structural driver. One needs to expand this analysis to the provincial level to account for greater spatial variation in vegetation dynamics, go beyond the linear and quadratic specification of this EKC and use more remote sensing data for ecological monitoring, and look at non-linear threshold effects that could indicate an EKC turning point for land-based indicators not captured by this national-level linear and quadratic specification.

Authors Contribution

Sonia Nisar: conducted data analysis and modeling
Mukamil Shah: supervised the methodology and edited the manuscript

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest w.r.t the research, authorship and/or publication of this article.

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